INVESTIGATION OF WATER LEAKAGE MECHANISM IN THE KARSTIC DAM SITE, SAMANALAWEWA, SRI LANKA

By

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Chapter 1

Introduction

1.1 Background

The Samanalawewa reservoir is one of the largest and important reservoirs in Sri Lanka. It has been built on, Walawe river, one of the five main rivers in the country. The construction works of the whole Samanalawewa project including the reservoir was implemented during 1986 to 1991. However the reservoir developed a leakage in its right bank during initial filling conducted in 1991. In parallel with the leakage problem, an increase in the right bank ground water level, pausing stability problems, was also observed. In two occasions attempts were made to remedy the leakage however the leakage did not stop. The main difficulty in remedying the leakage is due to the inadequate knowledge on the leakage mechanism. The site being a typical case of karstification, exhibits complex ground conditions and peculiar hydrogeological characteristics. In this study an attempt was made to examine the behaviour of the right bank and to establish the reservoir leakage mechanism. This thesis is fully based on the detailed study carried out on the reservoir leakage problem.

1.2 Objective and scope of the study

As mentioned earlier, in two instances attempts were made to remedy the reservoir leakage incurring huge costs. However they failed to seal off the leakage successfully. The main difficulty in remedying the leakage is due to the inadequate knowledge on the leakage mechanism, i.e. locations of leakage inlets (ingress areas) and leakage paths. Therefore the main objective of this study is to understand the reservoir leakage mechanism, by evaluating the right bank behaviour using the ground water level measurements and leakage flow data collected over a period of fifteen years (from 1991 to 2005) since initial impounding. In this regard the data collected from more than fifty observation wells and piezometers installed in the right bank were used in the evaluation. Thus the study includes

a) Investigation of the reservoir leakage mechanism
b) Modelling of the reservoir right bank system using the two tank model
c) Quantitative assessment of the leakage inlets(ingress areas)
d) Detection of probable locations of leakage inlets

Further it is considered that such a study will be of assistance in a future remedial measures planning exercise.

1.3 Samanalawewa hydro electric project

Samanalawewa reservoir is the key element of the 120 MW Samanalawewa Hydroelectric Project, which was implemented to harness the potential energy of the Walawe river.

The Walawe river and one of its tributaries katupath Oya river flow in a south easterly direction in parallel valleys from the mountains of central Sri Lanka. The horizontal separation of the two rivers is only about 6 km while the vertical difference in their levels is over 300 m. The Samanalawewa project utilizes this head difference in the generation of energy, by creating a large reservoir along the long narrow valleys of the Walawe river and the Belihul oya river, another tributary.

The reservoir was built at a location near the town Balangoda, 160 Km south east of the capital, Colombo. The Figure 1.1 shows the location map of the project. The project area is located by the latitudes 6°35’N to 6°42’ and longitudes 80° 43’E to 80° 50’E.

The reservoir has been formed by constructing a 100 m high 530 m long rock fill earth core type embankment dam at a location about 300 m downstream of the confluence point of Walawe river with its tributary Belihul oya.

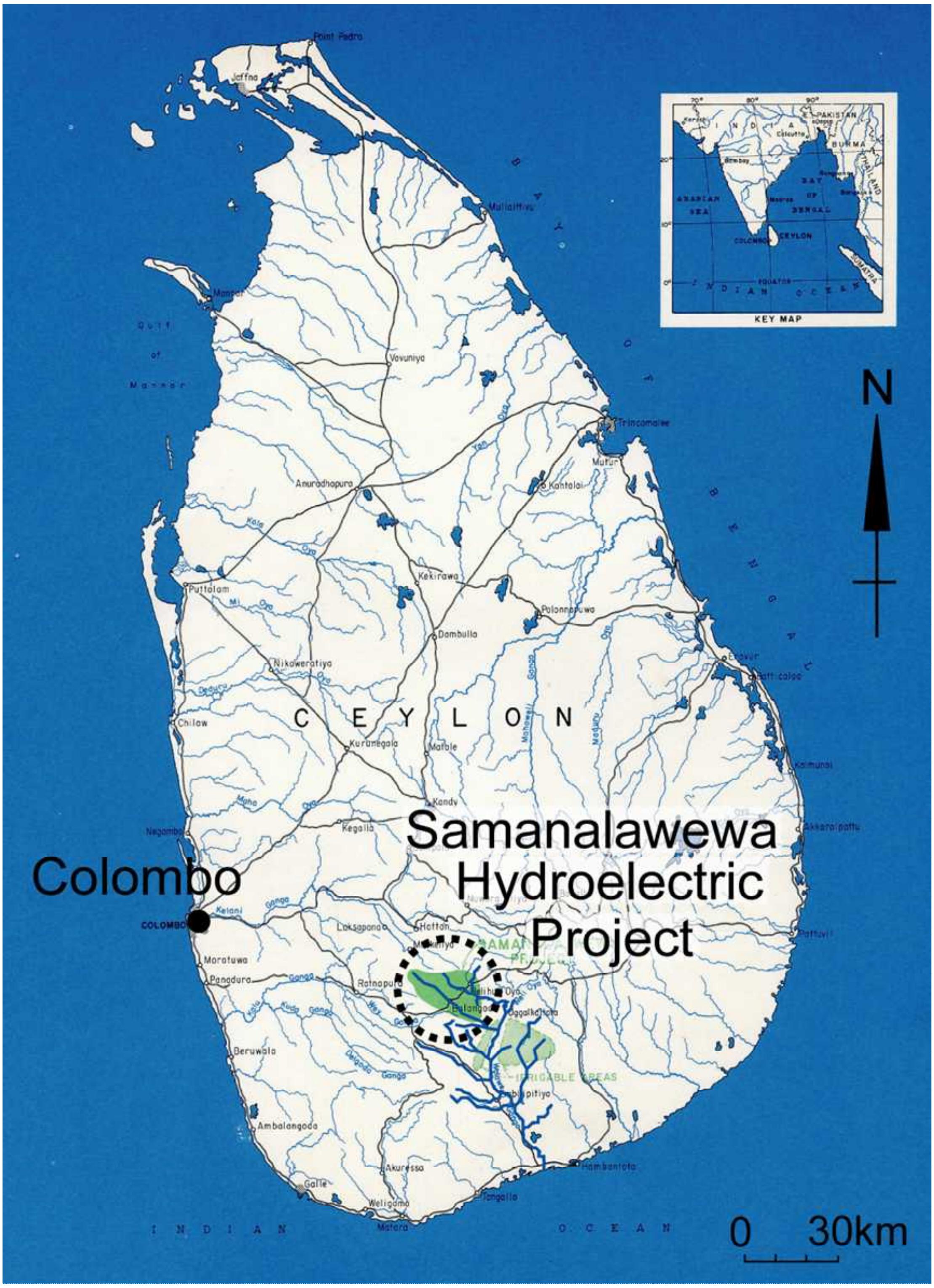


Figure 1.1 Location Map

The other elements in the project are the water intake structure on the Walawe river, 5.35 km long 4.5 m diameter headrace tunnel, 120 MW surface power station, housing all electro-mechanical equipment including two turbine generator units of each 60 MW capacity, two 132 kv transmission lines and 650 m long, open tail race canal releasing water back to katupath oya. The Figure 1.2 shows the general layout of the project. The Table 1.1 shows the main features of the Samanalawewa hydroelectric project.

The detailed investigations of the Samanalawewa hydroelectric project have conducted over a time period of 30 years since 1958, under the guidance of number of national and international consultants. However it was not possible to implement the project until the necessary funds and approvals were secured in 1986.

1.4 Reservoir leakage problem and the remedial measures

1.4.1 Initiation of the leakage

As discuss in following sections the right bank exhibits specific hydrogeological characteristics which are typical of karstified ground. The initial signs of such characteristics were surfaced, with the discovery of the low and flat ground water level in the right bank during site investigations. Also during construction stage most of the observation wells in the right bank indicated a flat and low ground water level.

The construction works of the Samanalawewa project was started in year 1986 and the main works was completed in 1991. Initial impounding of the reservoir was commenced in June 1991, immediately after completing the dam main construction works. During this impounding, the right bank ground water level started to respond to the rising reservoir water level (this will be discussed in detail later). At the same time the reservoir started to leak from its right bank. The leakage appeared as a small spring in the right bank about 300 m down stream of the dam and the flow rate measured to be about 5 lit/sec while the reservoir water level was at 398 m amsl (reservoir water depth of 16 m).

Table 1.1 Main features of the Samanalawewa hydroelectric project

Reservoir catchment area	341.7 km^2
Average annual run off	561 mill m^3
High water level	460 m amsl
Design flood water level	460.7 m amsl
Minimum operating level	424 m amsl
Reservoir gross storage volume	278 mill m^3
Reservoir live storage volume	218 mill m^3
Reservoir dead storage	60 mill m^3
Dam rock fill central clay core type	
Dam crest elevation	463 m amsl
Dam height	100 m
Dam length	530 m
Dam body volume	4.5 mill m^3
Spillway gated over flow with flip bucket	
Spillway design discharge	3600 m^3/s
Number of gates	03
Size of gates	11 m wide X 14 m high
Sill elevation	446.7 m amsl
Low level outlet capacity	70 m^3/s at FSL
Low pressure waterway : concrete lined tunnel with circular shape	
Diameter	4.5 m
Length	5,159 m
Intake sill level	416.75 m amsl
Surge chamber type : restricted orifice with concrete lined	
Diameter	18 m
Height of chamber	88 m
High pressure waterway : steel penstock	
Number of lines	one
Diameter	4.5 to 3.85 m
Length	840 m
Power station : open air surface type	
Installed capacity	120 MW (60MW x 2)
Rated head of the turbine	320 m
Rated discharge	42 m^3/s
Average annual energy expected	405 GWh
Tail race : open canal type	
Length	585 m
Power transmission : 132kV double circuit	
Length	17 km to Balangoda

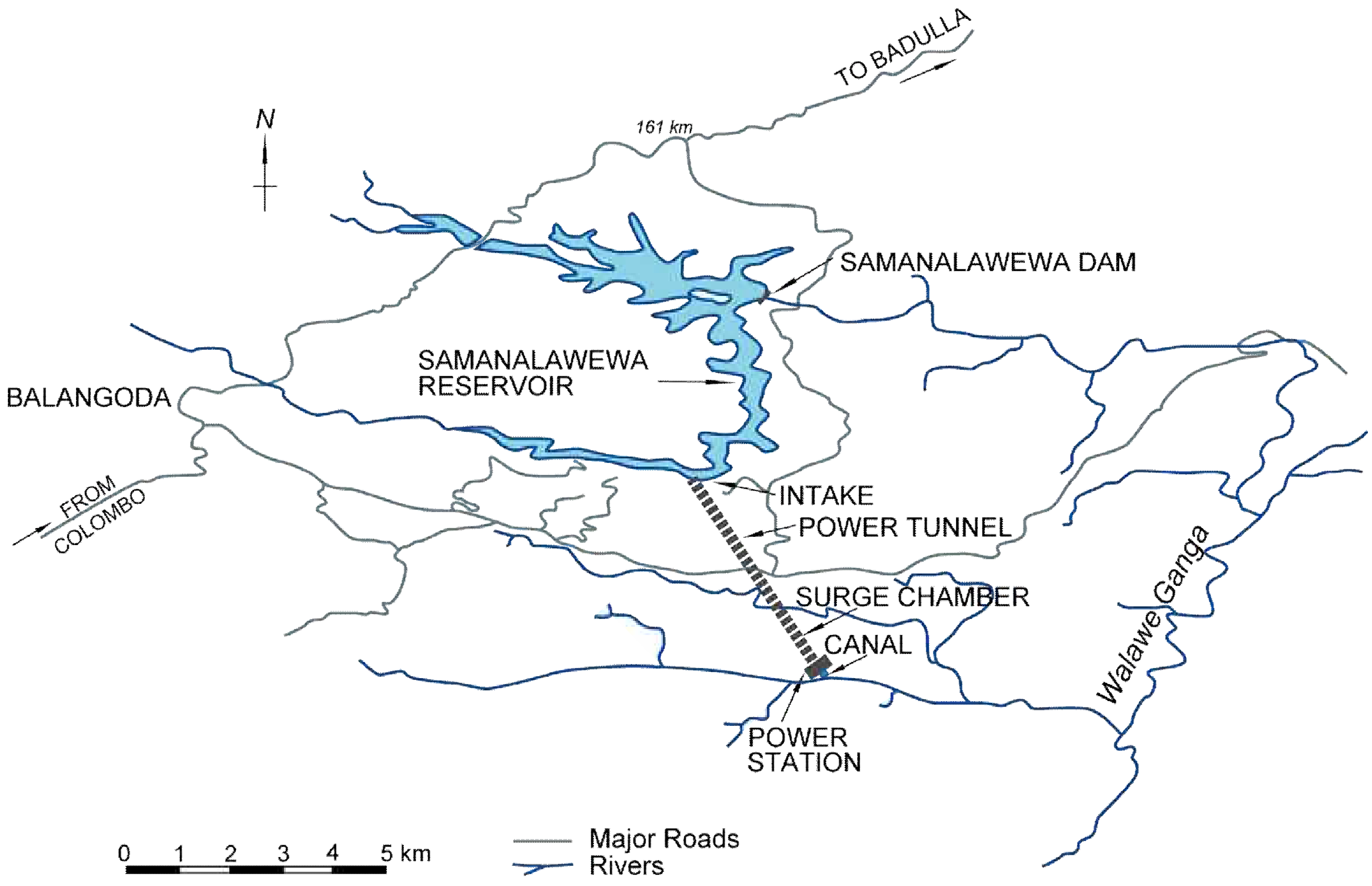


Figure 1.2 Project lay out

At this stage the reservoir impounding was suspended as the reservoir was not water tight and remedial measures were sought for.

1.4.2 Grout curtain construction

As a remedial measure, construction of a grout curtain was decided as the best solution to seal off the leakage. Thus based on the additional geological investigation results a 100m deep 1315 m long grout curtain was designed with the aim of cutting off the main leakage paths passing across the right bank. According to the geological findings, the potential leakage paths were considered to be along the karstic rock units and through major faults existing in the right bank. Thus a 1315 m long and 100 m deep grout curtain cutting across the fault zones and running in to the right bank was constructed. The grout curtain consumed 13,450 tons of cement and involved 53,600 m of drilling for grouting. Average cement consumption was 256 kg per meter depth with a maximum recorded grout take of 15.5 tons/linear meter. A set of grouting adits (marked as D(b), I, H, and F in Figure 1.3) was used in this construction. The Figure 1.3 and 1.4 shows the plan layout and longitudinal cross section respectively of the grout curtain. The Table 1.2 shows the grout takes and drilling involved in the grout curtain construction.

Number of stand pipe piezometers (named as RBS series) was also provided both upstream and down stream of the grout curtain in order to monitor the ground water levels upstream and down stream of the grout curtain.

On completion of the right bank grout curtain construction works the official impounding of the reservoir was commenced in March 1992 coupled with an intensive monitoring programme to observe the right bank behaviour closely. With the commencement of the impounding, reservoir started to fill gradually to be ready for feeding the 120 MW power station, which was waiting for water to commence commercial power generation.

However with the rising reservoir water level majority of observation wells and piezometers installed in the right bank started to rise with no respect to their location being either up stream or down stream of the grout curtain. The ground water level shown by them was closely following the reservoir water level.

Table 1.2 Grout take and drilling involved in the grout curtain construction

Right bank grout curtain					
Location	Adit I	Adit H		Adit F	Check holes
Chainage (m)	1315-960	960-620	620-290	290-0	1315-0
Drilling (m)	3477	18564	9460	20238	1555
Grout take (tons)	308	4936	1525	6749	123
Average (kg/m)	89	266	161	334	79

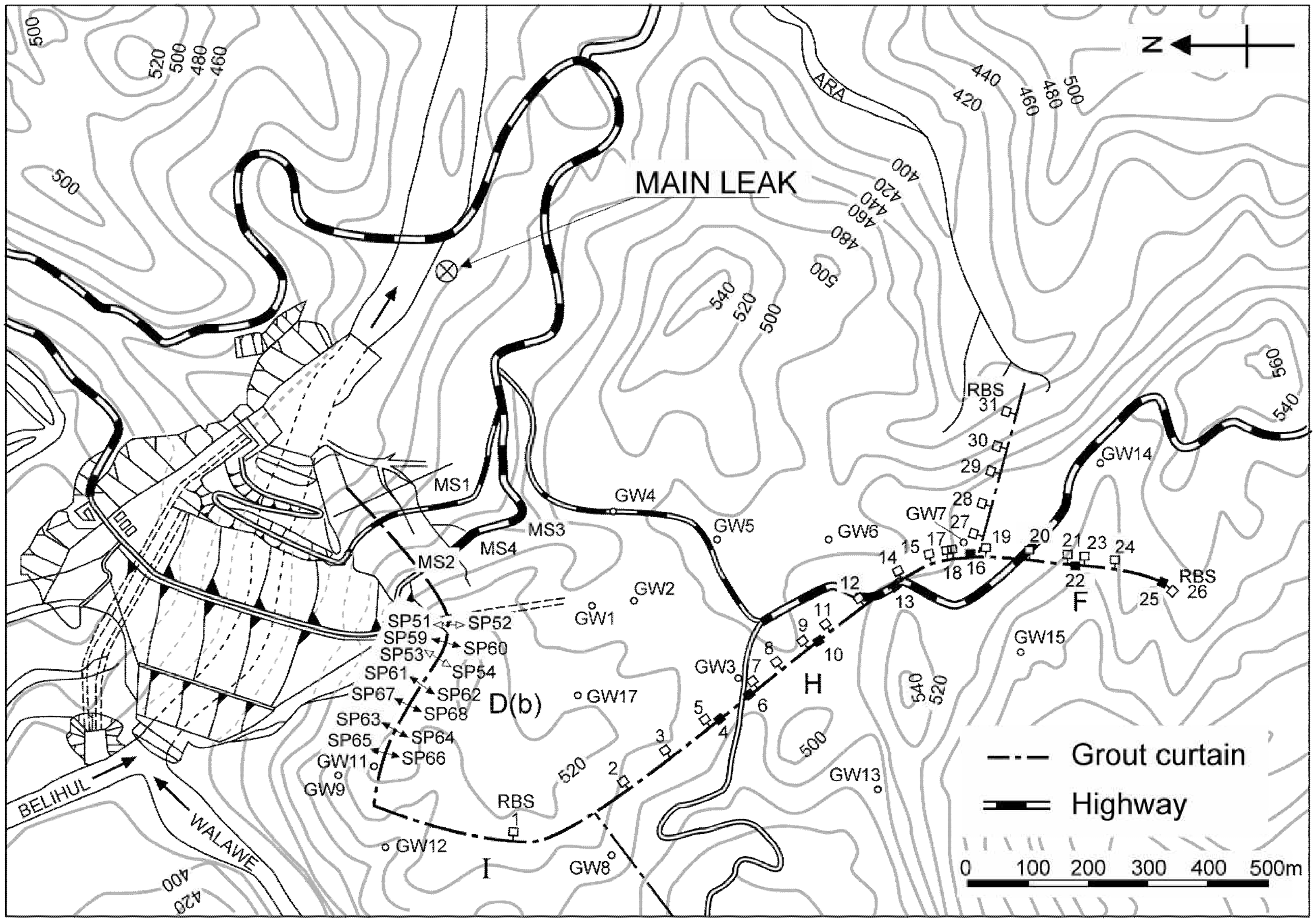


Figure 1.3 Plan view of the grout curtain

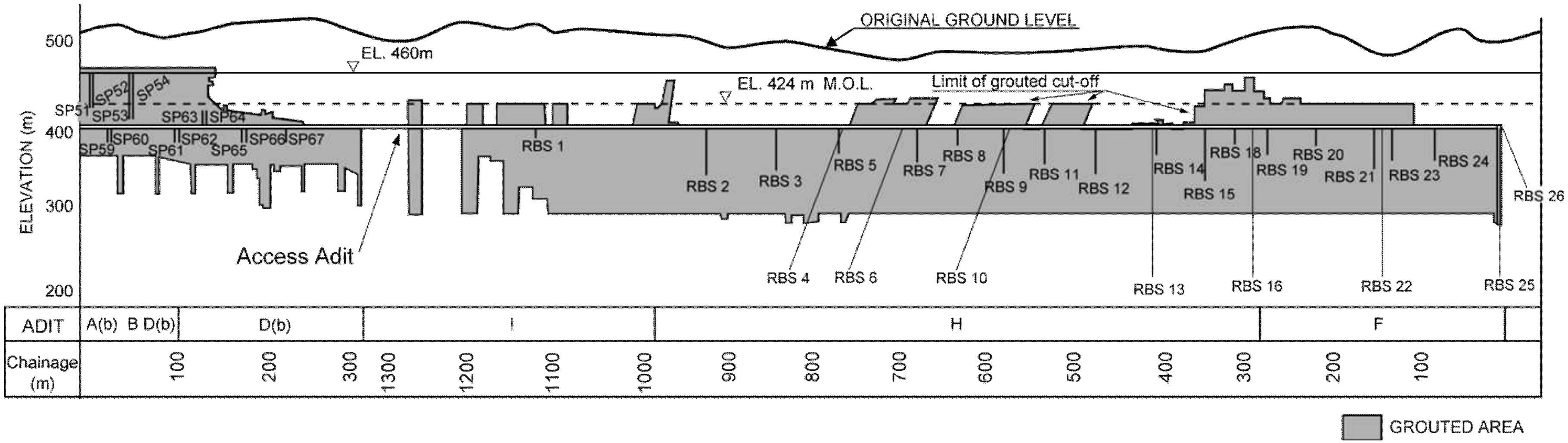


Figure 1.4 Longitudinal section along the grout curtain

Any change in the reservoir level was reflected in the ground water level by an equal amount with a 10-15 hour time lag. The reservoir leakage too reappeared as a small wet patch and developed to a level of a small spring, with the rising reservoir water level.

However reservoir impounding could not be continued for a long until a sudden burst in the right bank occurred in October 1992 forcing the impounding to be suspended. A sudden burst originated at the leakage outlet resulted in washing away of large portion of the right bank down stream face. An estimated 25,000 m^3 of earth and rock material was washed away within about 10 hours during this burst. The incident which was similar to a massive earth slip occurring broad day light caused the leakage flow rate to increase to 7 m^3/sec suddenly and later stabilized at 2 m^3/sec, still much higher than the initial leakage rate.

This burst also resulted in a sudden drop of ground water level shown by the majority of the observation wells and piezometers. All those observation wells and piezometers which were showing an equal ground water level, indicated a 25 m drop instantly and then stabilized at a level about 10 m below the reservoir water level after about 10 hours . The leakage flow rate and ground water level behaviour during the burst are discussed in detail else where. Further since this incident the total leakage flow is emanating from a single outlet, which is an opening of a karstic cavity or channel (marked as main leak in Figure 1.3), lying at the base of the crater (ground elevation 392 m amsl) created by the burst.

On suspension of the impounding, the reservoir water level was lowered and maintained at a safer level until the remedial measures are implemented. As a safety measure to ensure the right bank stability against slope failures due to the leakage and high ground water pressures, installing of large number of pressure relief holes, slope stabilization around the leakage outlet and in the eroded areas were carried out. At the same time the construction of a permanent leakage measuring weir and channelling of the leakage flow were also carried out.

This burst in the right bank resulted in relieving the excess ground water pressure, which has been building up with the continuation of the impounding. This incident also resulted in enforcing restrictions on the reservoir operations by the government and the lending agencies until proper remedial measures are implemented and the safety of the right bank ridge is assured. Thus the reservoir water level was maintained at 430 m amsl elevation i.e. at a level 30 m below the maximum reservoir water level since the burst incident until the leakage remedial measures are implemented.

During the period following the burst detailed investigations were carried out to study the leakage problem with the objective of deciding on the suitable remedial measures to arrest the leakage. The detailed studies included drilling of another set of exploratory drill holes, geophysical investigations (seismic refraction survey) and water chemistry analysis. All of the above studies were conducted as a part of the intensified study to establish the reservoir leakage mechanism and to plan the appropriate remedial measures. The new exploratory holes drilled were completed with permeability measurements and at the end they were converted to act as observation wells for monitoring the ground water level behaviour.

The geophysical investigation involved a seismic refraction survey conducted under water in the suspected ingress zone lying along the riverbed. Within this 700 m long suspected ingress zone, lying 1km upstream of the dam along Walawe river the 3 geological faults intersect the riverbed.

Under the water chemistry analysis, water from the reservoir, different observation wells, pressure relief holes, leakage outlet, etc. were collected and analyzed for their chemical composition i.e. basically the Cation and Anion composition. Later the obtained results were compared to determine the water sources exhibiting similar composition. On that basis an attempt was made to identify the leakage paths by connecting the locations with similar chemical composition.

1.4.3 Earth blanket construction

Based on the above mentioned additional investigation results the second attempt of the leakage remedial measures i.e. construction of an earth blanket was planned. Under this work it was planned to dump graded earth material under water along the 700 m suspected ingress zone, where the three major faults are crossing the riverbed. (see Figure 1.5) Later in 1998 the construction of the earth blanket in the reservoir bed under water was implemented using two 125 m^3 capacity bottom open type barges. The dumping was carried out in the suspected ingress zone. Further the dumping was arranged to perform in stages, starting with an initial trial dumping and then to dump in two stages depending on the success. The idea of the trial dumping was to establish the proper material gradation, appropriate moisture contents, barge flap opening times etc. which would result in making an ideal blanket under water. In this trial dumping 25000 m^3 of material was placed on the suspected ingress zones. After establishing a proper dumping mechanism in the trial operation the dumping of the first phase was carried out. In this phase 50,000 m^3 of earth material was dumped over the suspected ingress zones.

However even after dumping about 500,000 m^3 on the suspected ingress areas no response in either the leakage flow rate or the ground water level was observed. Leakage flow rate and the ground water level were monitored on a continuous basis to see the effects of the dumping exercise. With no signs of response in the monitoring parameters the dumping in the suspected main ingress areas, was suspended and instead dumping in the surrounding areas was carried out. Thus when dumping in an area known as “Block X” suddenly the right bank ground water level started to drop. With the dumping in this block X area the right bank ground water level dropped by about 10m at once. However the reduction in the leakage flow rate was slight and amounted to 200-300 l/sec. Continued dumping in this area did not result in any further improvement. Similarly after attempting at other areas along the riverbed and in the absence of positive results, the whole earth blanket construction operation was suspended in 1999.

No further progress was made in remedial measures after earth blanket laying works suspended in 1999. Since then the reservoir has been operated in its main objective of power generation while the reservoir leakage continue to exist at a rate of 1.80 m^3/sec. the leakage flow rate changes slightly with the changing reservoir levels reaching almost 2.00 m^3/sec at reservoir full supply level of 460EL. The ground water level in the right bank ridge too continue to behave in a similar manner maintaining a total head difference of about 22 m and showing a flat water table along the right bank ridge up to a distance of about 2.5 km.

1.5 Current situation

Since the end of earth blanket construction concluded in 1999 to date no further remedial measures were attempted. The reservoir has been feeding the power station, engaging it in full commercial operation, amidst the leakage, which continues to exist with a flow rate varying around 1800 l/sec depending on the reservoir water level. Further the right bank ground water level too fluctuates while registering a head difference of about 20-22 m with reservoir water level through out.

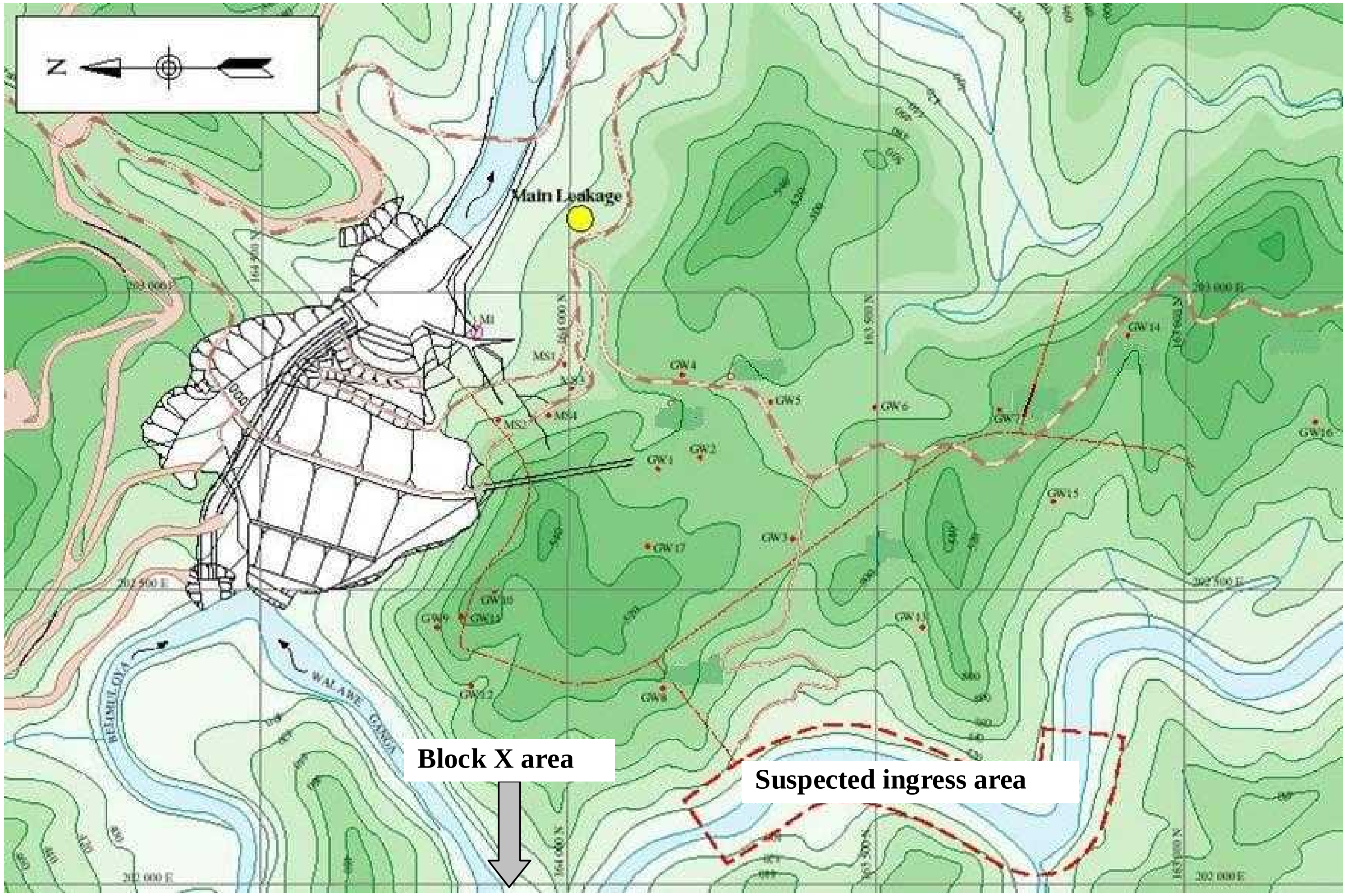


Figure 1.5 Suspected ingress area for earth blanket construction

Chapter 2

Literature review

2.1 General

Karst is a landform that is formed primarily by dissolution of carbonate rocks such as limestone, dolomite, marble, gypsum and salt. Features of karst landscape include sinkholes, caves, sinking streams and large springs. This topography comprises more than 25% of the Earth's surface. Karst areas are extremely complex and produce great variety of topographical, geological and hydrogeological conditions (Milanovic` 2004). Many problems have developed with structures such as dams, reservoirs and tunnels built in karst areas world over. Many of such problems have been due to the failure in understanding the geological and hydrogeological characteristics caused by karstification. There are large number of dam and reservoir projects built world over on karstic ground. Some of them are suffering from leakage and other associate problems due to the unfavourable karstic features at site. There are also number of successfully completed dams and reservoir projects built on karstic ground. They have been thoroughly investigated and the karstic characteristics of the site have been well understood before hand. Therefore it is necessary to get a basic understanding of the karst and the process of karstification. Under this chapter on literature review, basics of karst geology studied are being presented.

2.2 Origin of Karst

The term karst originates from the geographical name of the northwestern region of Slovenia near the Italian border, which extends from Austria to Ljubljana. More than 700 years ago, the people in this region used the Slavic word *kras* and the Italian word *carso*. (Gus'ic Be, Gus' ic M, 1960). Both expressions are of Indo-European origin, coming from the word "*kar*", meaning rock. The word "*krass*" originates from the word *kar*. With the germanization of these words, the term *karst* was formed. The unusual natural features of the karst region become known as "karst phenomenon" and so too, by extension did similar features found else where in the world.

The concept of karstification denotes the multitudes of geological processes that destroy soluble rocks, thus forming unique morphological features and specific types of porosity, or a specific hydrogeological environment (Milanovic 2004).

2.3 Karst types

Several authors have classified karst according its morphological features, structural factors, geographical position, and depositional environment of the carbonate rocks followed by number of other factors. Since none of these classifications are based on numerical values or on parameters that can be quantified or expressed by exact laws, any one of karst classifications can by judged as acceptable or unacceptable depending upon individual preferences or the aspects stressed by each individual's classification system.

In 1926, Cvijic provided one of the first classifications of karst. Using the morphological features as the base, he divided karst in to three types named as holokarst, merokarst and transitional type.

Holokarst (complete karst): develops in areas comprised entirely of soluble carbonate rocks. It is characterized by the existence of surface and underground karst phenomena, making feasible further development and the creation of new karst phenomena. The vast bare and rocky land, without arable land and with or without the presence of vegetation gives very specific appearances to holokarst regions.

Merokarst (incomplete karst): has many properties of non karst regions. Carbonate rocks (bituminous, marleous, dolomitized) were far less subjected to the process of karstification. Therefore the karst phenomena are infrequent and the depth of karstification is limited. Carbonate sediments are covered with arable soil and with vegetation. Bare, rocky land surfaces with karrens are practically absent. Dry and blind dolines with chains of sinkholes are uncommon and karst poljes are absent. This type of karst is frequently called covered karst.

The transitional type karst has a degree of karstification as to fall between holokarst and merokarst. It is mainly found in limestones that are isolated by impermeable less soluble sediments. Underground karst forms are well developed but karst poljes are absent.

The classification of karst is very important from the hydrogeological standpoint. It is based upon differences in essential geological characteristics and above all, upon lithological and structural characteristics. According to this classification, there are two clearly different types of karst: platform karst and geosyncline karst.

Platform karst is characterized by horizontal or gently sloping strata and by platform relief. Carbonate rocks usually contain a higher percentage of Marley material; therefore their karstification is hindered. These sediments are often found tightly imbedded between impermeable rocks or lying over impermeable rocks. Because of the absence of differential tectonic movement, regions of platform karst tend to be devoid of ruptured elements that provide the main lines or directions for karstification process.

Geosyncline karst develops in distinctly folded and ruptured or faultered carbonate rocks. With favourable climatic conditions, the synclinal fold regions are excellent environments for the maximal karstification process.

The main difference between the platform and geosyncline types of karst is that hydrogeological relations in the geosyncline type of karst are more complicated and the karst process are more active than they are in platform karst. The geosynclinal karst regions can be clearly distinguished from platform karst regions by the quantity of dissolved materials water carries from the karst medium. The solution activity of the carbonate rocks in geosynclinal karst far exceeds the solution activity of karst platforms. (Komatrina M. 1973)

Herak (1976) proposed a tecto-genetic approach to classification of karst terrains, distinguished by the morphological and hydrogeological differences. According to him, it is possible to identify two main tecto-genetic types of karst: epiorogenic karst and orogenic karst.

Epiorogenic karst develops within the carbonate or other soluble rocks deposited in an epi-continental sea or under freshwater conditions. This type of sediment and karst develops in horizontal or sub horizontal layers. Folds are regular and faults often have a regional extension.

Orogenic karst develops in carbonate and other soluble rocks that were subjected to strong tectonic (orogenic) movements, very often with over thrusts as extreme structural forms. The thickness of rocks and their position in a geosynclinal sequence determines the variety of types.

2.4 Karstification process

The term karst is directly associated with the carbonate rocks, more specifically the limestones and dolomites, though karstification occurs within the formations of gypsum and salt. Nevertheless, karst became a synonym of carbonate rocks (limestones and dolomites) including all their varieties and conglomerates with carbonate matrix. Although the limestone is the most important rock in which karstification takes place, the dolomites susceptibility to karstification depends upon the thickness and position within the geological structure.

Limestones are most representative of all the carbonate rocks. They are largely composed of the mineral calcite ($CaCO_3$, calcium carbonate). Very rarely are limestones composed only of pure calcite. Most often they contain certain percentages of clay, bituminous matter, magnesium, silica, sands and other minor components. Depending on the quantity of these inclusions, limestones may be classified as shaley, bituminous, dolomitic, siliceous, sandy etc. The solubility of limestones in karstification increases with their purity.

Evaporite rocks (gypsum and salt) are the most soluble of the common rocks. Salt (halite) solubility in water is 35% by weight at 25°C and increases at higher temperatures. The karstification process is identical to those found in carbonate rocks and forms the same type of karst features typically found in limestones and dolomites.

The formation of caverns and channels is the direct result of chemical dissolution, which at a certain stage of the process could be supported by an erosive action of water. As turbulence of water is increased, the quantity of solute is also increased. According to the experimental work of the White, the following has been concluded: if the Reynolds's number increases from 250 to 25,000, the rate of solution increases by approximately a factor of three. Fully developed turbulence on the face of a spinning disk appears as a Reynolds number of about 50,000. However, there is no evidence that a dramatic increase in flow velocity and turbulence increase the dissolution process, it seems that a change from laminar to turbulent flow represents the initial factor in cavern growth.

Temperature is also an important factor controlling the dissolution process of limestones. Castany (1963) established that 1 litre of water at 0°C can dissolve four to five times more limestone than at 30°C and six times more than water at 40°C.Corbel also provided the same conclusions. After detailed investigations he concluded that karstification is more rapid in cold climates with higher snow precipitation than in the regions with hot weather. Further according to him, the rate of erosion, including both mechanical and chemical, in low mountains with 1000mm to 1600mm of precipitation and a cold climate is 160mm per 1000 years. During the same period in a hot climate, the erosion is 10 times lower (only 16mm). In plains regions with 300 to 500mm of precipitation with a cold climate, the rate of erosion is 40mm per 1000 years, compared to only 4 mm in a hot climatic regime.

2.5 Role of tectonics in karstification

Karstification is a result of water penetrating in to permeable and soluble rock masses. Solubility and permeability are equally important factors. The basic factor of permeability in the carbonate rock mass is jointing.

Limestone and dolomite rocks are very brittle, especially if they are thick layered, benched and massive. Intensive tectonic processes will produce extensive joint systems that provide access to water that can migreat in to deeper sections of the thick rock mass. Fragmentation of masses, resulting from tectonic processes, represents the most important factor in karstification, which operates both horizontally and vertically.

The most important joint systems are those that have been formed by tensile stresses usually resulting in block separation. These joint systems are always formed in anticlines and in the deeper parts of the synclinal folds. During the process of folding under the influence of strong shear stresses, consolidated bedding planes could not provide sufficient shearing resistant to the applied deforming forces. As a result, bedding plane joints are formed that play an important role in karstification. These joints are usually part of a joint system that cut through rock layers and jointly form a continuous and well defined network of secondary openings. Although secondary by origin, this porosity represents the controlling force in the karstification process. The most influential joints within this secondary porosity network are those that have the greatest separation (cross sectional area) and depth, that is the ones that provide easier access for gravitational water.

Stress release, which produces relaxation joints, also plays an important role in karstification. Relaxation joints are formed in planes perpendicular to the axis of the maximum compressive stress after its action has been terminated. Following the release of stress, a rock mass will attempt to assume the same state that existed prior to the application of the stress. As a result, stress release joints are formed. They are concentrated within or near the surface zones, specifically in areas where erosion process were the most extensive. These areas of extensive erosion are usually within deep river valleys, along canyons, around dolines and deep sinkholes, etc. Their sides increase the formation of the stress release joints. It is not easy to determine the depths to which these joints are developed. Some authors report depths of 100 or more.

Surface cracks that are the result of exorgenic process also play a key role in karstification. These cracks, together with stress release joints, comprise an extensive network of openings that intercept surface water and convey it into and through the lower (tensile and stress release) joint systems down to the deeper portions of the carbonate rock mass. By comparison, the joints that only extend through single rock layers have very little effects. Thin layered, bedded and laminated limestones are less brittle than benched and more massive limestones. In addition, they are usually shaley or contain shale interbeds, and therefore the jointing is less obvious.

Water movement within all these joints is caused by gravity. The velocity and quantity of the flowing water depend upon the size of the channels and fractures and their degree of interconnection. Scientists disagree about the minimal opening width required before free movement of water by gravity occurs through these joints.

According to Lehman (1932) water cannot circulate through openings that are less than 1 to 2 mm wide. Later Sokov stated that experiments proved that openings with a width of only 0.5 to 2.0 microns contain free gravitational water.

Zones where two or more faults come together or intersect (e.g. along shear zones) are the most susceptible to karstification. Sink holes together with the chain of small ponds, are commonly formed at the land surface above and along these zones. In deeper portions of the carbonate rock mass, cavern prevail. The distribution of vugs, caverns and smaller solution channels follow the direction of the tectonic or lithographic discontinuities. This is particularly true for the case of interbedded channels.

Surface depressions substantially increase karstification. Parizek (1972) analyzed the effects of tectonics fragmentation on the underground flow of soil water and ground water within karst regions. He outlined a variety of ways in which permeability and porosity development is enhanced by for carbonate rocks located in valley bottom settings when compared with the same rock located beneath adjacent topographically high regions. Well yield data obtained from wells completed in valley bottom settings nearly universally show a statistically significant increase in yield when compared with yields of wells located in adjacent uplands no matter what the rock type. However the most spectacular increases in yield were noted for carbonate rocks located in valley settings where karstification tends to be tenser.

Once surface depressions and tributary drainages are initiated above joints, bedding plane openings, faults and fracture zones, pounding of surface water, or surface run off is concentrated. This promotes increased infiltration and solution attack of the underlying bed rock along the same secondary tectonically induced openings that localized these surface depressions to start with. Some karst valleys were show to be predisposed (80 to 90%) by tectonic features. As the erosion process progresses, valleys are formed that may eventually intersect bedrock exposing cay-filled joints, solution zones, or open channel ways. Concentrated infiltration and recharge within swallow holes and CO_2 enriched residual soils and alluvium sediments are further increased as their watersheds increase in area. Rocks beneath valleys and surface depressions consequently have a high initial fracture permeability, which naturally leads to acceleration in karstification processes. Ground water flow lines converge within rocks near ground water discharge areas, thus increasing the volume of ground water available for karstification. In time, vast volumes of surface runoff may enter ponors developed along the valley floor as the water table drops below the valley floor sediments and the valley becomes under drained.

Karstification depth that is the depth to which the soluble rocks were exposed to the karstification process may vary widely. Existence of the karstified rocks has been established in Dinaric region by drilling to a depth of 2236 m, i.e. 1600 m below the mean sea level.

There is no distinct underground surface for the depth of the karstification process. The transition zone represents the surface below which there is no karstification. This is called the base of karstification.

By investigating the formation and distribution of karst porosity associated with karst springs, Le Grand, and La Moreaux concluded that karstification decreases with depth and that "progressive concentration of water in the upper zone of saturation produces master conduits there, but causes no appreciable increase in flow and solution at great depths (Figure 2.1). The solid line in the figure represents a common condition, whereas the dashed line and dotted line represent less common but not unusual conditions.

Observations of the variation of karstification and permeability development versus depth have been made for a large region of dinaric karst. The results of permeability investigations from 146 deep observation wells drilled in regions with elevations of 200 m 1000 m above mean sea level have been utilized in this analysis and presented as shown in Figure 2.2. It is evident from the figure that, generally speaking karstification decreases with depth. The zone of greatest karstification, and at the same time the highest porosity, is at the depth ranging from surface to 10 to 20 m (epikarst zone). Karstification of this zone is not adequately shown on the graph because far more than 60% of observation wells within this zone were not tested for permeability.

If we assume that karstification decrease with depth according to an exponential law, then

$$n = a.e^{-bH}$$

Where n is the index of karstification, H is the depth in meters, e is the natural logarithm, a and b are coefficients.

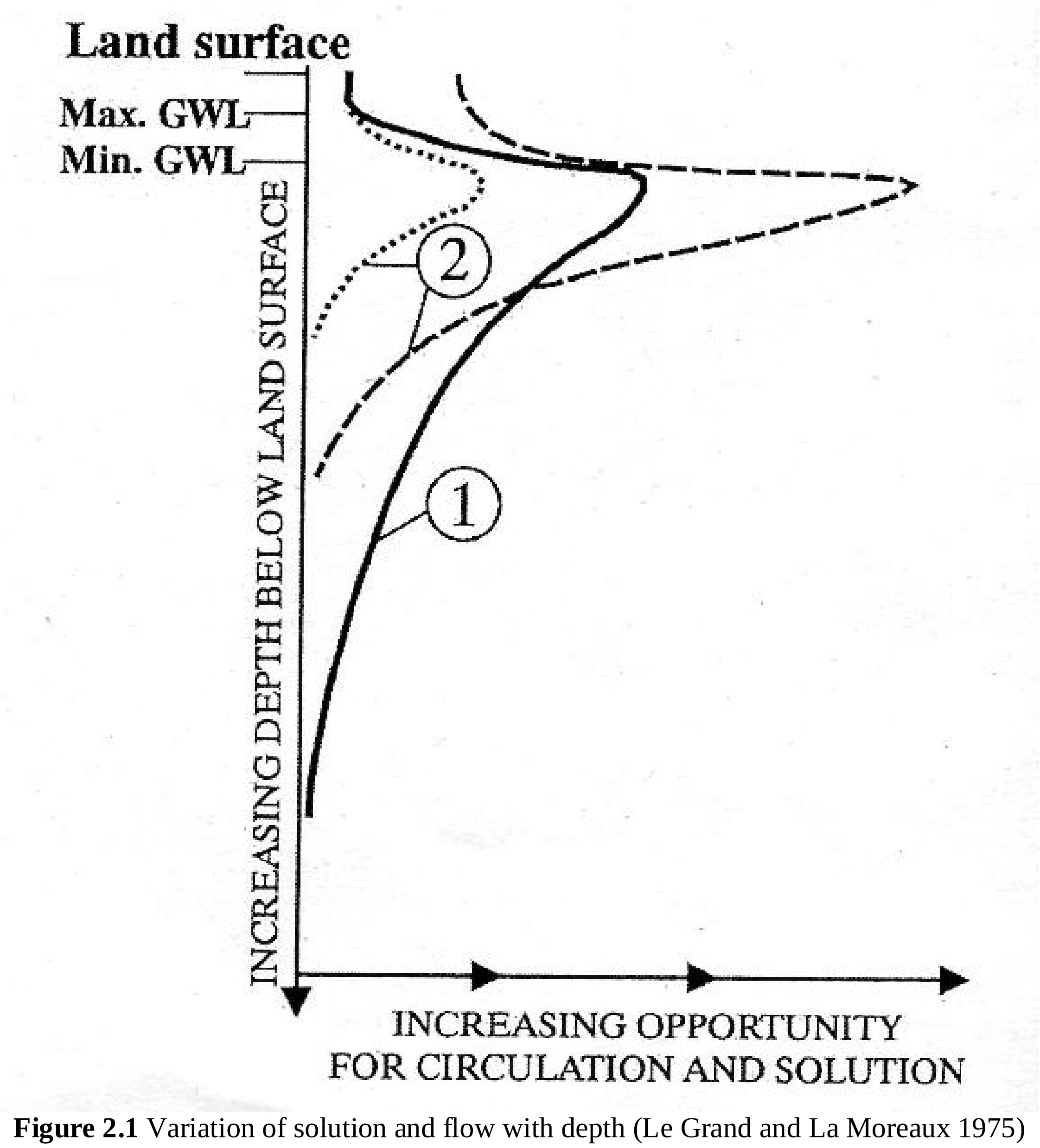


Figure 2.1 Variation of solution and flow with depth (Le Grand and La Moreaux 1975)

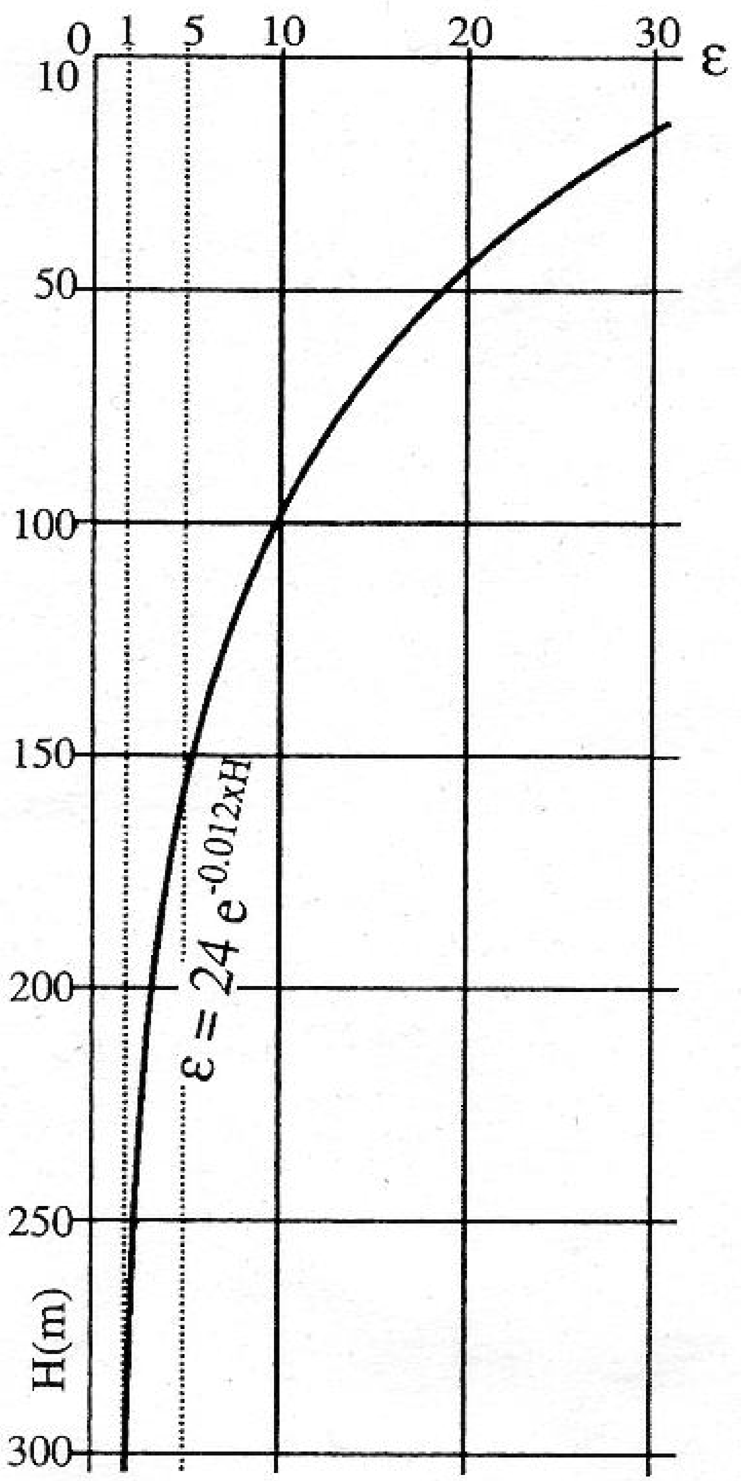


Figure 2.2 Relationship between the karstification and the depth (Le Grand and Las Moreaux)

For the graph shown in Figure 2.2, the variation of karstification with depth can be expressed by

$$n = 23.9697e^{-0.012H}$$

it is evident from the same graph that karstification in the surface zone of 0 to 10 m is about 30 times greatr than at a depth of 300 m. For depths greater than 300 m, the index of karstification approaches its minimum value, somewhat greater than zero. The karsts of Dinarids, Helenides and Taurides are well known for very deep karstification. The zones where the karstification extends to depths to 300 to 500 m and locally even deeper are not very large and do not involve a considerable rock volume. This karstification is associated with tectonic zones and has been expressed in two dimensions.

The highest intensity of karstification is in the aquifer section with the largest storage capacity in the zone of water table fluctuations (Figure 2.3). According to the graph, the zone with most storage is the section of water table fluctuation. Karstification decreases below the lowest ground water levels. The base of karstification and the minimum water level coincide. Generally the slope of the base of karstification leads to the zone of the aquifer discharge. The most active karst channels are directly above the base level. The existence of karst drains below this level is not excluded, but they are rare and of limited transport capacities. Vlahovic (1975) analyzed many exploratory borings from Yugoslavia. He was able to prove that in the zone above the lowest levels of the water table there are 3.3 times more karst channels and caverns than in the zone below these levels.

2.6 Groundwater movement in Karst

Movement of ground water through karstified rocks is quite different to from that of through non karst terrains. This movement is a specific hydrogeological characteristic of karst terrains. Almost all underground and surface phenomena in karst are by their origin, related to the presence and movement of water.

Interest in obtaining a detailed understanding of all kinds of water occurrence and movement within karst regions has existed for a long time.

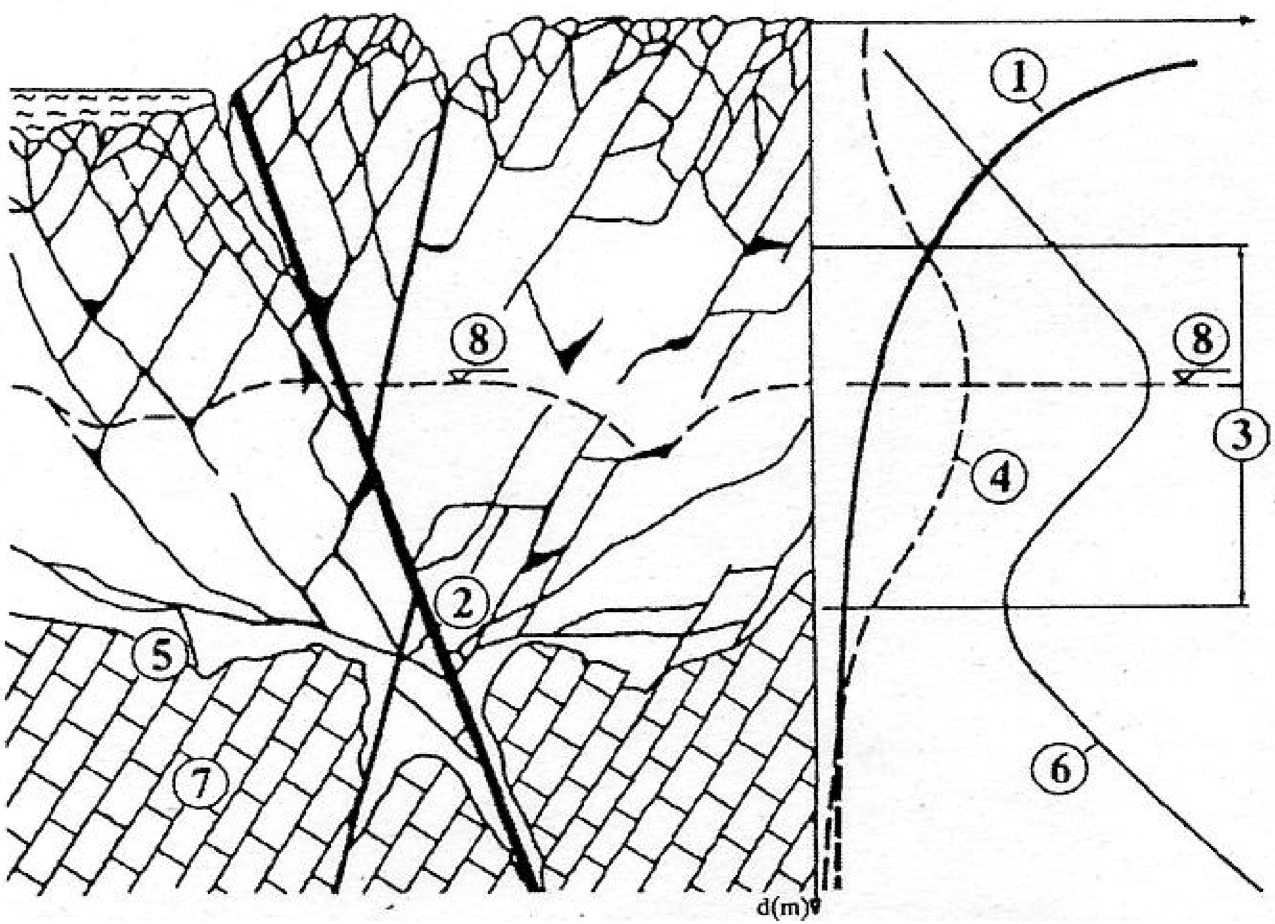


Figure2.3 Schematic representation of the depth of karstification: ***1***. relationship between karstification and depth: ***2***. zone of base flows: ***3***. zone of water table fluctuation: ***4***. curve of vertical distribution of active karstic porosity: ***5***. base of karstification: ***6***. curve of electrical sounding: ***7***. non karstified limestone: ***8***. level of water table (Le Grand and La Moreaux)

In contrast to other geological terrains, it is more difficult to establish the relationships that govern the circulation and storage of water in karst terrains. For this reason, all scientists who studied karst formulated theories based on their own specific experience that are in many instances either opposite or controversial. The best known theories were established at the beginning of this century.

According to the theory of the geographer Alfread Grund, there is a uniform water-bearing horizon in karst: the aquifer. He separates two zones of underground water: stagnant zone and karst water. Stagnant water does not move since it occurs in cracks and caverns of karstified rocks located at great depths. The water table of this stagnant zone gently slopes toward the sea. Above this zone is a zone of moving (flowing) water which Grund named as karst water. Its free surface is also dips toward the zone of outflow that is the sea, but at a much higher rate than the dip on the stagnant water table.

The Austrian geologist Friedrich Katzer, in contrast, believed that the flow of ground water in karst terrains takes place predominantly through systems of caverns and channels. According to katzer, there are underground water courses through karst channels, cracks and caves that are “at one instant interweaved and branched out, and oddly interconnected at another instance independent from one another”. According to the Katzer, separate systems of underground flows, which are also areas of chemical erosion, prevail in deep karsts where development of the karst process has not reached the impermeable base.

Jovan contemplated three hydrographical zones with different types of circulation and considered them to be a direct consequence of the evolution of the karst process. Those three zones are (1) dry, (2) transitional, and (3) zone with continuous circulation of water.

The dry zone is located directly below land surface. It is characterized by an abundance of dry caves, channels and cracks through which water moves almost vertically down ward toward the transition zone. Ground water may flow in some of these channels and caves during rainy seasons.

The transitional zone is characterized by permanent and periodic hydrological phenomena. During periods of precipitation, percolation of water in to deeper portions of the carbonate rocks is either slowed down or completely terminated within this zone.

Groundwater is concentrated in this zone where active flow takes place. The transitional zone is located above the bottoms of karst depressions. During rainy seasons, the development of springs is a characteristic of these depressions.

The zone containing continuously moving water is located beneath the level of karst depressions. A substantial quantity of water from this zone flows in the direction of the water table. Thus, water movement is slowed down. This zone contains scattered enlarged cracks, and the phenomenon of siphonal circulation is often encountered. Since the aquifer discharge capacity is reduced, groundwater levels rise during heavy precipitation when the size of this zone is increased at the expense of the transitional zone. A similar relationship exists between the transitional and dry zones.

These three zones are not clearly distinguished, and their position can be changed. They closely follow the evolution of the karst process and move downward, one at the expense of the other. During the process that causes each zone to be lowered, the surface of the terrain is also being lowered due to denudation. In the last phase of development, only the dry zone remains in the lowered karst. Super position of these zones is always dependent upon geological structures. They are expressed less in shallow karst and more in deep karst. Jovan’s theory has been accepted by many researches as being the closest to reality.

2.7 Karst aquifers

Karst aquifers are non homogeneous underground reservoirs in which water collects in networks of interconnected cracks, caverns, and channels. The free water table of the aquifer is not a well defined continuous surface. It has regional as well as local dips. In general the entire aquifer dips towards the base of erosion, where water drains from the collector under the influence of this base level.

The position of the base of erosion is an essential factor in the determination of the dominating direction of underground circulation. Lithology, faults, and structures are also very important controllers of underground water flow, but their function is essentially less important than the role of the base level of erosion. With respect to its importance in the formation of hydrogeological characteristics of karst regions, the base of erosion can be divided in to three groups.

The first group includes the absolute erosion base level. These are the sea basins, specifically the zones between the sea level and the deepest submarine springs occurring in the region. The second group includes the major erosion base levels for continental regions. These are the deepest river valleys and canyons. The third group contains local erosion base level. These are karst poljes, river valleys of higher elevation (dry or with flow), dolines etc. Local base levels have effects on small regions and are always used for conveyance of the temporarily stored water. From a karst development standpoint, these bases are very important because they have a considerable influence on regulating the evolution of karst aquifers.

Karst conduits with high transmission capacities represent local levels of erosion for the surrounding rock mass where fracture type porosity predominates. Water table or piezometric surface is formed and frequently change under the influence of these local base levels. Thus the water levels observed in piezometers or bore boles essentially depend on the conditions that exist within the nearest water filled conduits.

The Figure 2.4 shows schematically a change of piezometric line under the influence of three drains located at various elevations. During the highest groundwater stage shown as piezometric level I, water table location depends upon the capacity of a drain as revealed by the piezometer located nearest to the drain. The water table in these piezometers will be at a greater depth than the free water surface. It will be deeper (h_I) in piezometer I than in piezometer 6(h_I'). Alteration of Δh of the piezometric line can also be observed in piezometer 4 since this piezometer is directly connected with drain b, which contains actively flowing water and is thus under hydraulic influence. Instead of the expected level H, the level of H+ Δh will be measured at this greater depth. The piezometric line is altered locally as indicated by position I_a. At this time, piezometer 4 acts as a drain for the part of the aquifer in the immediate vicinity.

By further lowering of the water table, drain b also gradually begins to function as the dominating erosion base level. At one moment, the piezometric line assumes position II. In borehole 5 the effect of drain c(base flow) starts to be recognized so that the measured level in this piezometer is deeper for h than the expected groundwater level h. The measured water level is observed at depth h + Δh. The effect of drain c on borehole 5 is not directly connected to the existing drain b.

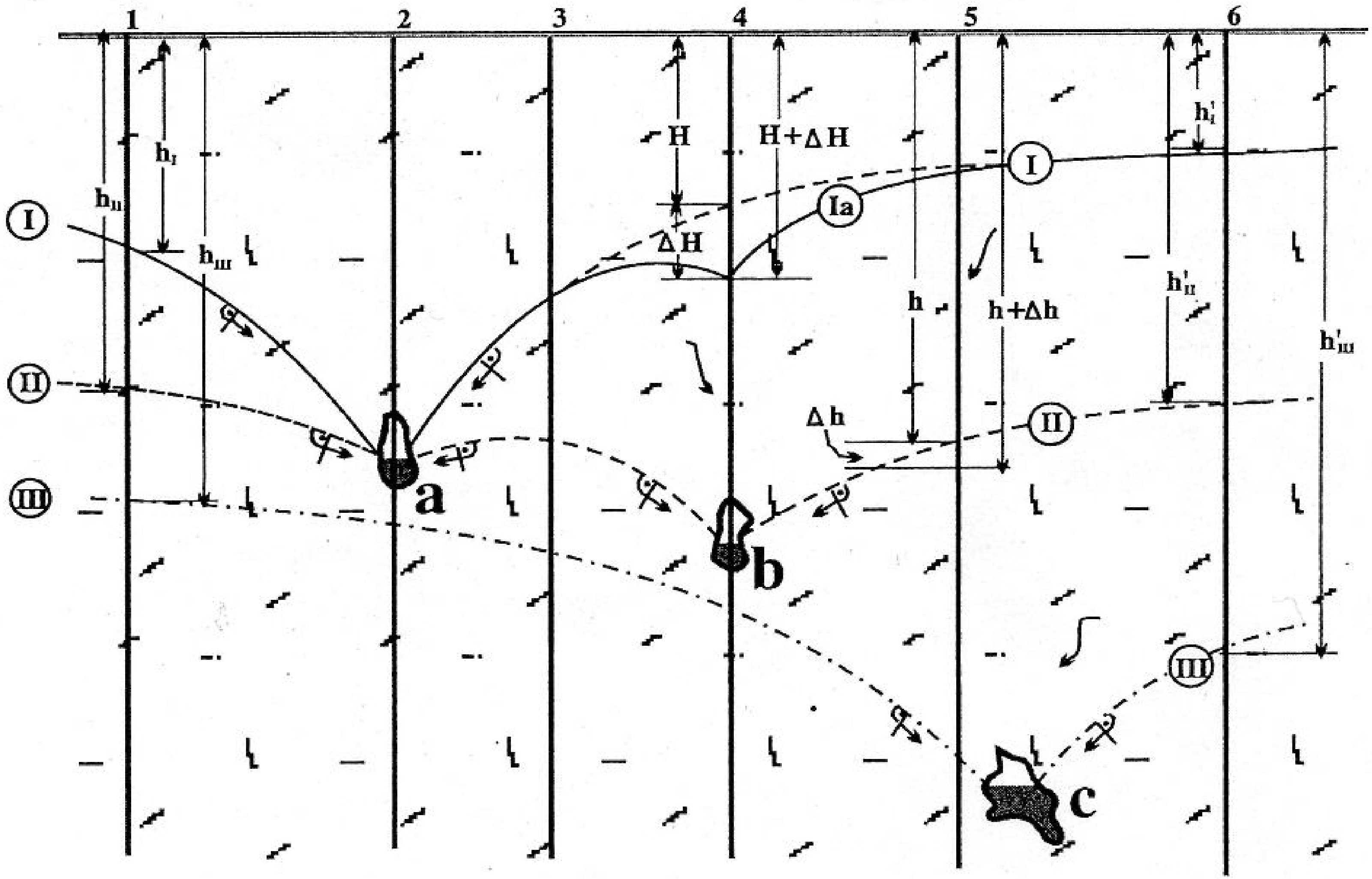


Figure 2.4 Position of piezometric line in Karst aquifer

Finally under the influence of drain c the piezometric line III is formed and is quite different from the previous line. The measured level in borehole 1(h_{III}) is now considerably higher than in piezometer 6(h'_{III}) because it is closer to the momentarily actual base of erosion.

2.8 Evolution of Karst aquifers

Karst aquifers develop in response to dynamic phenomena that operate in time and space. Their geometry changes very rapidly, which in turn changes hydrodynamic regimes of the aquifers. All of these changes represent a uniform process: the evolution of karst aquifers.

Karst aquifer evolution is based on the tendency of karsts to adjust their water level to the zone of discharge in reference to the base of erosion. That water trend is directed at first to the nearest base of erosion. As soon as this base level is reached, the process continues further in so far as there is another lower base of erosion. By lowering the groundwater level within the aquifer to a greater depth, channels of higher elevation begin to lose their permanent function in the drainage system. The highest channels remain constantly above groundwater level and stalactites and stalagmites start to form in them.

Epirogenic movements govern this competition, which is reflected in changes in hydrogeological water sheds and shifting of terminated drains. As a consequence of this karst evolutionary process, ground water levels continuously are being lowered, often to the sea level, through a rearrangement of surface drainage systems. In the final stage of this evolution, the surface drainage system completely disappears. Temporary river flows, dry valleys and periodically flooded poljes are the only phenomena that remain at the surface.

The karst process destroys the individual surface drainage systems under some geological conditions: it connects them and transforms them into one single catchment area. Under some tectogenic conditions, this process destroys vast water abundant surface catchment areas and creates from them a few smaller karst catchment areas.

2.9 Fluctuation of the water table

The large dimensions of karst channels, their good interconnections, high water level gradients and the high permeability of surface zones enable fast filling and emptying of these water collectors, that is fast formation of aquifers and nearly equally, their fast drainage. Relatively small total porosity and extraordinary feasibility of water circulation generally result in very fast fluctuations of aquifer water table, showing high amplitudes. The aquifer reacts quickly to high precipitation in the rainy seasons, sometimes as in 10 to 15 hours and in some cases even faster. For example in a karst site in eastern Herzegovina of former Yugoslavia, a sudden water level rise of 90m within 10 hours of heavy precipitation has been reported.

Two periods with different characteristics of fluctuation can be distinguished in many karst terrains: the wet season, with the aquifer's water table showing continuous vertical changes, and the dry season characterized by slow but constant lowering of the aquifer's water table. The dry season is usually called the recession or depletion period of the aquifer.

2.10 Average velocity of flow in Karst

Several hundred investigations have been performed for the purpose of finding the major routes of underground water circulation. By analyzing data from those experiments, it was concluded that the average flow velocity varies within a wide range of 0.002 to 55.2 cm/sec. These extreme values represent velocities that rarely occur. It is evident that water in karst terrains most frequently has an average velocity of about 5 cm/sec.

The results of recent investigations by various agencies have shown that the karst circulation velocity varies with the hydrologic conditions of the surface of the terrain, in other words, it depends on instantaneous saturation of the aquifer. During the dry season and low aquifer water table, water circulation in karst systems is characterized by a slow movement of aquifer water. Water waves labelled with dye take half to one fifth less time to travel the same distance during the season of high hydrologic activity.

Chapter 3

Samanalawewa dam/reservoir area ground conditions

3.1 Back ground

Topographically and geologically the Samanalawewa site area is highly complex. Having subjected to number of tectonic activities and to karstification, a phenomenon observed in soluble rocks, the site shows specific geological characteristics.

The Samanalawewa hydroelectric project has been studied during several periods since the first investigation conducted in 1958 after identifying the hydro potential of the Walawe river. Detailed site investigations were conducted by several national and international consultants from USA, Switzerland, Japan, Australia, USSR, and UK. In 1986, about 30 years after the initial studies, with the beginning of project implementation, an additional geological investigation and a review of the previous investigations were conducted. This chapter summarizes the general ground conditions, and detailed geological findings based on these studies.

3.2 Regional geology

The island of Sri Lanka is composed of Pre Cambrian rocks consisting of a complex series of metamorphic rocks of 1000 my to 2500 my old. They account to more than 90% of the surface. Further they could be classified in to two distinct groups, the Highland series and the Vijyan series (Vitanage 1972).

The Highland series (granulite facies) consists of a succession of typical meta-sedimentary rocks, quartzite, marble, white granulite and granulitic gneiss, charnockite (hepersthene granites) and gneiss, garnet–sillimanite-graphite-gniess, garnet-biotite gneiss (leptinites) and biotite gneiss. The argillaceous rocks of the Highland series around south western area of Sri Lanka consist of more feldspathic and garntiferous rocks and the wollastonite and scapolite rocks (Adams 1929).

The younger Vijyan series (almandine amphibolite facies), which further sub, divided in to Eastern Vijayan and Western Vijayan, consists mainly of migmatitic microcline-hornblende-biotite-gneiss and calcareous gneiss. Marble and quartzite are rare and these Eastern Vijayan rocks occupy the Eastern and South-eastern lowlands and uplands. The Western Vijayan rocks are characterized by the occurrence of pink-feldspar-hornblende granites, migmatites and gneiss occur in northwestern and northern lowlands and uplands (Vitanage 1985).

The Precambrian rocks of Sri Lanka has been further sub divided in to three major units on the basis of lithology, structure and age as the Highland group of granulite facies meta sediments, the south western group (lithologically similar but still bearing the imprints of granulite facies metamorphism) and the Vijayan complex of migmatites and granitoids (Cooray 1982).

The most extensive sedimentary formation is the Miocene limestone in the northwestern area. Rocks of Jurassic age occupy a restricted outcrop area in the northwest. They are shallow water non marine deposits consisting mainly of shale and arkosic sandstone (Figure 3.1).

The structure and tectonics of the Vijayan series and highland series have major differences due to the thrusting of Precambrian meta sedimentary rocks of highland series, in to a series of regular folds of anticlinal and synclinal structures (Vitanage 1985).

The axes of those are nearly parallel to each other, but the plunge varies along several axes. The foliation or bedding planes of the rocks conform in most cases to the major folds, the dips are moderate to flat, and the axes of minor folds and lineaments are nearly always parallel to the major structures. In the Vijayan series, it is very difficult to determine a regular fold system, even though the dominant trend of the rocks is similar to that of the Highland group (Tennakoon 1987). Geological mapping along with photo-geological and satellite imagery studies have indicated the presence of a series of major lineaments both regional and local nature (Vitanage 1985).

The foliation planes are vertical or very steep and the axes of the minor folds plunge in a variety of directions.

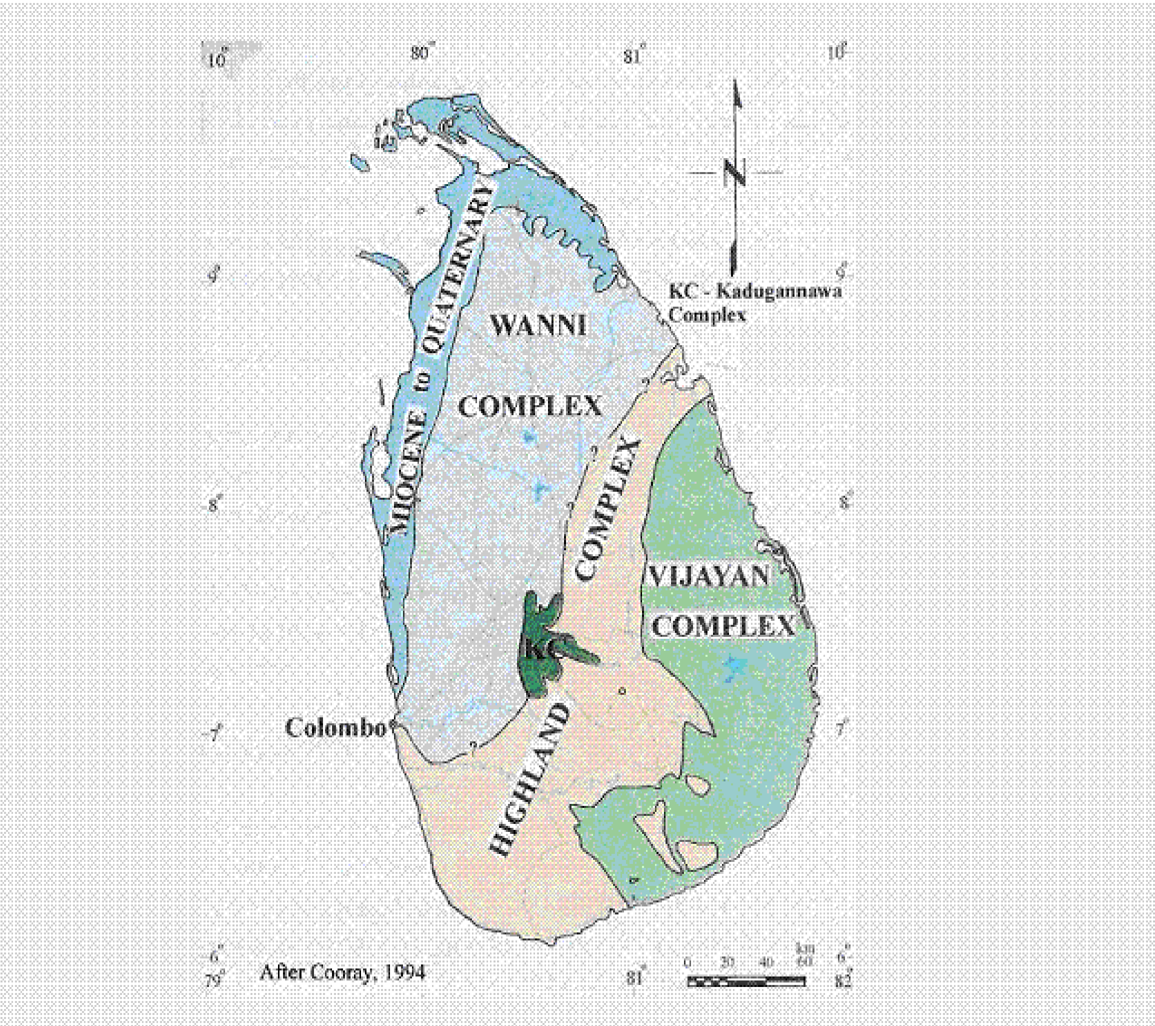


Figure 3.1 Geological composition map of Sri Lanka

Locally, where the rocks became granitized, the foliation planes and banding of the gneiss are highly contorted. Plastic deformation and flow folding appear to be the dominant processes.

3.3 Site Geology

3.3.1 General topography

The Samanalawewa dam site is located in the upper reaches of the Walawe river, which is a major drainage channel on the southern side of the central highlands and within the middle peneplain (Cooray 1984). The river course of Walawe appears to be strongly controlled by the geological structure or the joint systems of bed rock, commonly oriented either NWW-SEE or SSW-NNE to N-S. Belihul oya (river), a main tributary joins the Walawe river from the left side immediately up stream of the dam site. The dam is located approximately 250 m downstream from the Walawe/Belihul confluence. The extent of the dam is limited by this confluence itself and at its downstream end by the confluence of Matihakka Oya, one of left bank tributaries.

In the dam and reservoir area, the gradient of the river is very low. The river bed increases its gradient after about 500 m down stream from the dam site to flow down from the middle peneplain to the lowest peneplain. The river flow is less rapid in the vicinity of the confluence to the Walawe river and increase at about 500m down stream of the dam site.

The river valley within the dam site is relatively narrow with moderately steep banks. The left bank slopes at 23° – 26° and the right bank slopes at 28° – 32°. Several shallow ravines which carry water only during rainy periods are found on both banks. These ravines occur in pairs (one on each bank) and are perpendicular to the river. This indicates the possibility that they are controlled by the lineaments such as major joints or faults of the underlying rock.

The slope of the left bank was observed to be concordant with the dip of strata towards the river. The dip of the rock bed is reverse to the slope on the right bank.

The system of joints and faults in the bed rock control the course of the river and also the orientation of the minor tributary streams and gullies. Several shallow gullies detected around the dam site at nearly right angle to the Walawe river, were later found to be minor faults with displacements in the order of 0.5 m to 3 m.

The right abutment of the dam site rises up to a peak elevation of 545 m amsl and then descends to a low ridge which extending southward formed the right bank. There are important saddles at three locations on the ridge within a distance of 2.5 km from the dam site. These are named as saddle No.1, No.2 and No3 (Nippon Koei 1987). All those saddles are higher than the planned maximum water level of the reservoir (460 m amsl) by 20 to 60 m. Saddles of the same sort are found behind the left abutment too. However the ridge is far thicker in general to take in to account.

Rock outcrops are observed in many locations in the river bank within the dam site. Several outcrops of limestone are also present.

3.3.2 Stratigraphy and lithology of the project area

The bed rock of the dam site and surrounding area consists of highland series metamorphic rocks of the Precambrian crystalline complex (Vitanage 1972). Much of the bed rock is covered with quaternary deposits on the surface. The geological units are as described later in order from the older ages to younger ages.

The crystalline metamorphic rocks of Samanalawewa area belong to the Kaltota formation. The Kaltota formation is sub divided in to two members which are almost similar. The lower member is rich in crystalline limestones and in the upper member, quartzite bands are encountered more frequently. The kaltota formation consists mainly of four rock types, namely gneisses, granulites, quartzites and crystalline limestones.

Bed rock at Samanalawewa has been distinguished as a complicated inter-bandings of various sorts of gneiss and calcareous rock. These have been divided in to four zones depending upon the dominant kinds of rocks as follows.

a) Granulitic gneiss bed

This bed is composed of granulitic gneiss or leptinites intercalating often with biotite gneiss layers and occasionally with layers of quartzite and charnockite. These are the most commonly encountered rocks in the project area. The fresh rock is massive and hard with lustred bluish white color. The gneisses are foliated crystalline rocks composed mainly of quartz, feldspar and biotite. They also contain sillimanites, amphiboles and pyroxene. Among the gneisses the following types have been identified.

- Migmatized biotite charnockitic gneiss
- Migmatized garnetiferous gneiss

When the gneissic nature of charnockite gneiss is absent the rock is known as charnockite.

As this bed being exposed from the middle part to the top of the right abutment, the rocks are weathered to a considerable depth and discoloured to plain white or brown. They are deteriorated also by hydrothermal alteration to the depth of several tens of meters or more and the thickness of the granulitic gneiss bed is estimated as more than 140 m. Further this formation has been sub divided in to layers designated as GRA2, GRA3, GRA4 and GRA5 on the basis of charnockite and marble occurrence.

b) *Calcareous bed*

Though charnockite gneiss occupies a large part of this zone, the most significant from geotechnical point of view is marble bands which are frequently intercalated with other rock types. The rocks other than marble are dark green to dark gray and partly black. The biotite content is high in some horizons to form biotite gneiss. Granulite layers thinner than 2 m are also intercalated. Cavities due to solution of calcium carbonate are occasionally developed along these calcareous beds. Several sink holes and exposure of some of these cavities to the surface indicate the complexity of karstification. The thickness of this bed found to be between 30-50m.

The marble (metamorphosed limestone) is white and hard. In some parts diopsideis included and biotite is arranged along foliation as in calcareous gneiss. The thickness of the marble bands is less than 10 m and in the most cases less than 5 m. Approximately 30% of the total thickness of the calcareous bed is occupied by marble layers (Nippon Koei 1987). At some places the crystalline limestone is dolomitised and converted in to dolomites. In these rocks the carbonate content varies from 40% to 90%. Other constituents are diopside (3% to 40%), quartz (3% to7%) and plogophite (1% to 16%). Graphite and ore minerals are minor constituents. The crystalline limestones occur as bands and lenses of thickness ranging from 0.1 to 0.7 m.

c) Granulitic bed

The Granulite bed is located in the middle to lower part of the right abutment and in the area around the dam axis and upstream on the left bank. Component minerals are mainly feldspar and quarts with scattered garnets similar to the granulitic gneiss. Content of garnets in granulite rocks may range from 15% to 40%. Dark colored minerals are present in small amounts. Foliations do not exist or is very obscure and few parts are gneissore on the right bank where local warps of bedding planes are frequent.

The granulite is pale blue or pinkish tinged in colour, hard and massive rock in fresh condition. It is easily susceptible to weathering and the rock exposed on the ground surface is very often deteriorated in to reddish brown sandy soft rocks. Since this bed is only 15-20 m in thickness around dam axis, it could be utilized as a marker bed due to its relative homogeneity with the characteristic texture which is easy to discern.

d) Charnokitic Gneiss bed

Outcrops of this bed are developed from the river bed on the dam axis to the lower part of the slopes in the down stream area. On the left bank, where the bedding plane and the ground surface show nearly similar inclinations, a massive charnockite gneiss bed lies under the thin bed of the granulite which covers the ground surface only around the dam axis.

The features of the rocks resemble the calcareous bed in the upper horizons. But the proportion of the marble is lower. The dominant member is charnockite biotite gneiss. Other members are biotite gneiss, charnockite, granulite and marble. Foliation is commonly seen and the thickness deemed more than 100 m at the dam site.

The rock is composed of feldspar, quartz, hyperthene and biotite. Garnets are included occasionally and laminations with biotite develop at several millimetre intervals (Nippon Koei 1987). This formation has been sub divided in to CHA1 which is primarily charnockitic gneiss interbedded with crystalline limestone and to CHA2 which is additionally interbedded with granulitic gneiss.

Quaternary deposits consists of following three main types

i. Surface soil which is brown to reddish brown colored clayey sand or sandy clay, including organic matter, ordinarily not thicker than one meter.
ii. Talus deposits and slope-wash which are localized deposits on and at the foot of slopes
iii. River deposits which are only poorly formed on the bed of the Walawe river particularly along the trenches as a result of deep erosion along faults. The bed rock is well exposed and the alluvial deposits of sand and gravel, and sometimes clay are seen only in limited parts. Majority of the gravel are derived from charnockitic rock and 10-15 cm in diameter. A small extent of a low level terrace is located at about 10 m above the river bed at the confluence of the Belihul oya river (Nippon Koei 1987).

3.3.3 Geological structure of the project area

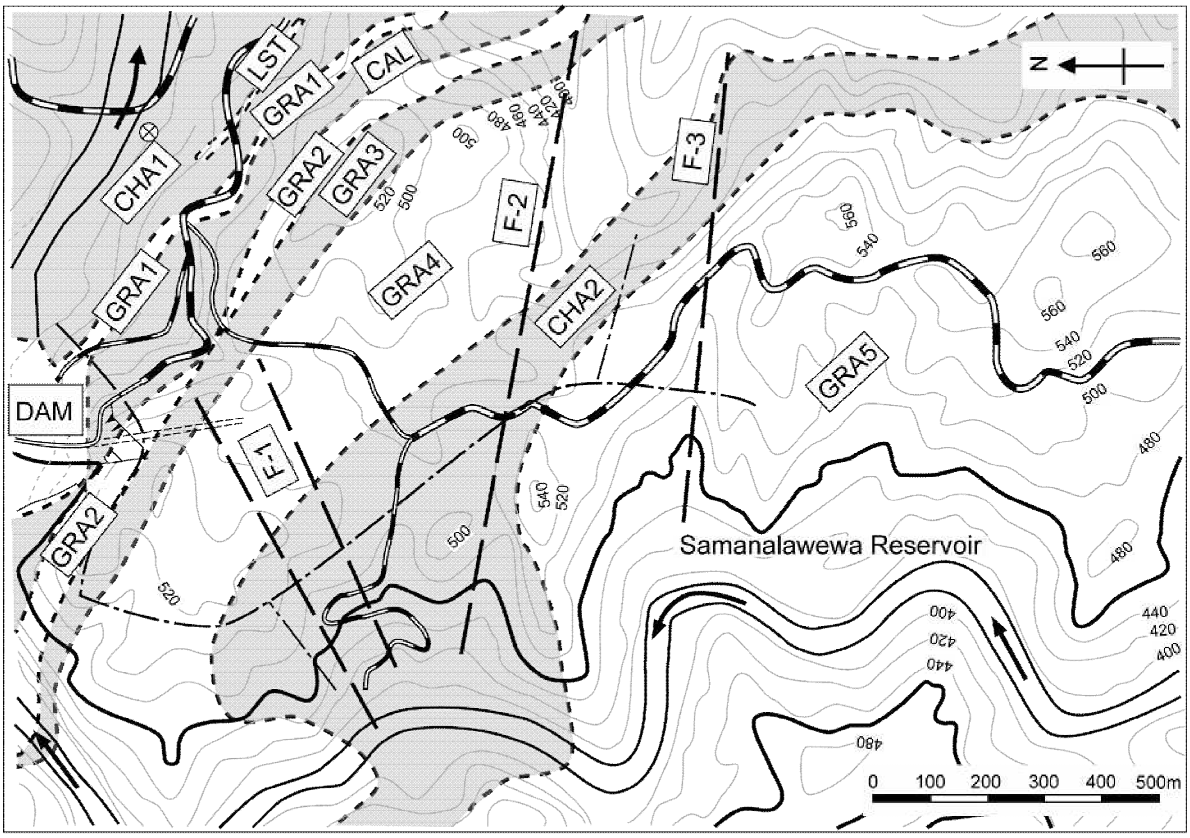
The main structural element of the Samanalawewa project area is the Balangoda synform which strikes from northwest to southwest (Vitanage 1985, Gunaratna 1990, Nagel 1992). The synform is asymmetrical with its axis plunging towards the NW at 15° to 20°. Its southwest limb dips at 35° to 40° while the northeast limb dips at 25° to 30°. The rocks folded in to the Balangoda syncline are cut by a number of discontinuity sets. There are mostly vertical and occasionally horizontal displacements along dislocations. Faults are mainly perpendicular but also parallel and diagonal to the strike of the fold structure. The majority of these faults dip steeply at 70° to 90° while a few are more gently inclined at 45° to 50°. the absence of reliable outcrops makes it impossible to accurately determine the precise throw of these faults. It is estimated that the thickness of crushed zones along individual faults does not exceed 10-15 m. Some of the crushed zones along faults weathered zones are developed. These faults daylight on the river bed and on the face of kaltota escarpment. In some cases movements of more than 100 m have been observed (Gunaratna 1990). The Figures 3.2 and 3.3 show a geological map of the area and a geological cross section across the right bank.

The “U” shaped Samanalawewa reservoir extends along the Walawe ganga for about 11 km and along the Belihul oya about 5.5 km. The reservoir is located in the core of the Balangoda syncline. The reservoir slopes are composed of interbedded benches of gneiss, granulites, limestones and quartzites. The thickness of the crust of weathering increases up ward along the slopes and is about 5-10 m at the normal high water level of the reservoir. A talus layer up to 4 m thick is present at the surface. Since, at the outer rim of the reservoir the rock strata dips towards the reservoir, any seepage path has to cross the bedding giving an added advantage with respect to reservoir water tightness. It is believed that the gorge slopes will be sufficiently stable except for small land slides confined within the weathered zone of the steep slopes.

3.3.4 Geology of the dam foundation and the right bank

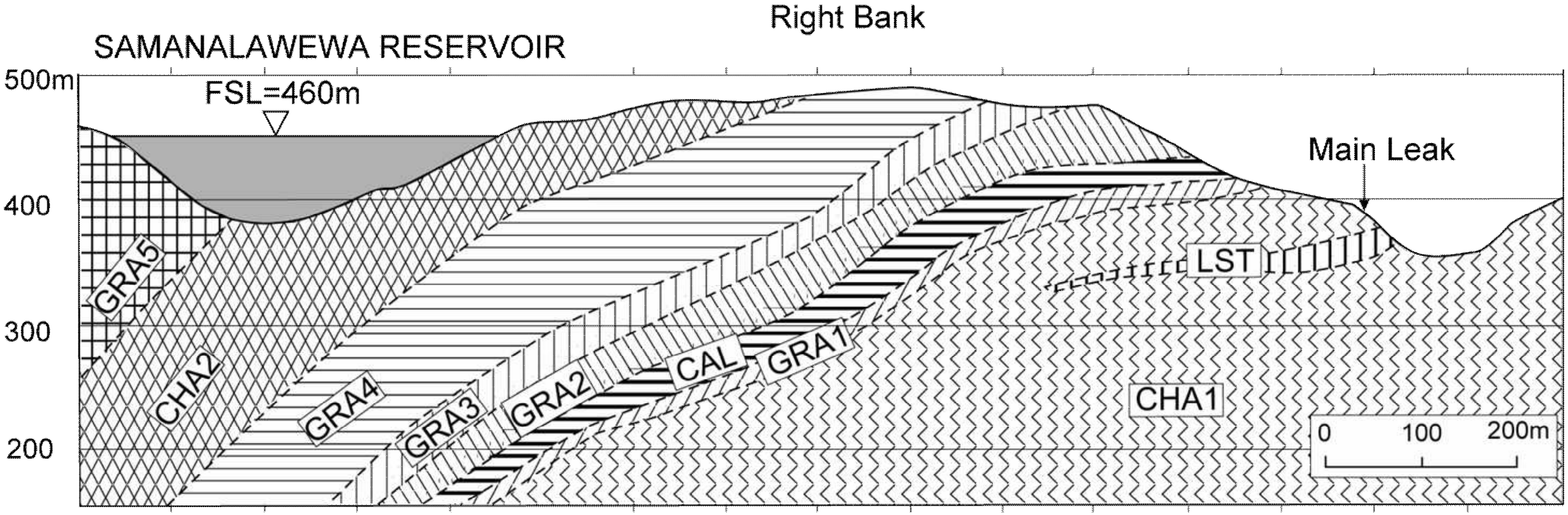
The dam site is underlain by Precambrian metamorphic rocks. The upper rocks of the synform are on the right bank and the lower rocks are on the left bank. The top of the right bank consists of interbanded granulite, garnet biotite gneiss, garnatiferous gneiss with thin intercalations and bands of charnockites, biotite gneiss and impure marble. The thickness of this formation is about 160 to 170 m (Perera V. 1993). This formation which called as the upper granulite bench (by Technopromexport 1978), was conveniently divided in to three other groups on the basis of charnockite and marble occurrence by the project consultants and the designers in 1988. The groups were named as GRA 2, GRA 3 and GRA 4. (see Table 3.1)

The dam site is located on the north-eastern slope of the Balangoda synform. On the left bank slope, the rock is characterized by south-westerly dips at angles of 25° to 40°. In the river, the dip angles are around 5° to 10°. These foliation angles result in an asymmetric valley with the left bank sloping at 35° to 45°.



F-1,2,3 Geological faults
GRA5 Predominantly garnetiferous granulitic gneiss
CHA2 Predominantly charnockite with marble,interfoliated granulitic and charnockite gneisses
GRA4 Interfoliated granulitic and charnockitic gneiss with this marble
GRA3 Granulitic gneiss
GRA2 Interfoliated granulitic and charnockite gneiss with this marble
CAL Interfoliated charnockite gneiss with marble layers
GRA1 Garnetiferous granulite
CHA1 Predominantly charnockite with marble,interfoliated granulitic and charnockite gneisses
LST Pure,impure marble
⊗ Main leak

Figure 3.2 Site geological map



GRA5	Predominantly garnetiferous granulitic gneiss
CHA2	Predominantly charnockite with marble,interfoliated granulitic and charnockite gneisses
GRA4	Interfoliated granulitic and charnockitic gneiss with this marble
GRA3	Granulitic gneiss
GRA2	Interfoliated granulitic and charnockite gneiss with this marble
CAL	Interfoliated charnockite gneiss with marble layers
GRA1	Garnetiferous granulite
CHA1	Predominantly charnockite with marble,interfoliated granulitic and charnockite gneisses
LST	Pure, impure marble

Figure 3.3 Geological cross section perpendicular to the right bank and across the leakage outlet

Table 3.1 Description of rock stratigraphy at site

Main rock bed classification	Designation	Description
Upper Granulitic Gneiss bed	GRA5	Predominantly garnetiferous granulitic gneiss
	GRA4	Interfoliated granulitic & charnockitic gneiss with thin limestone
	GRA3	Granulitic gneiss
	GRA2	Interfoliated granulitic & charnockitic limestone
Calcareous bed	CAL	Interfoliated charnockitic gneiss and marble
Lower Granulite bed	GRA1	Garnetiferous granulite
Charnockitic gneiss bed	CHA2	Predominantly charnockitic with limestone
	CHA1	Predominantly charnockitic with limestone,interfoliated granulitic and charnockitic gneiss

At the foot of the right bank towards the hill, two small folds with axes northwest-southwest running sub parallel to the river were encountered. In addition to these foldings a number of fault systems were identified which are oriented at NW-SE, WNW-ESE and NNE-SSW (Gunarathna 1990).

Based on a review of many right abutment core drilling records, Cooke in their review panel report, concluded that the core of the right abutment ridge contains a substantial amount of hard metamorphic rock although locally fractured to a greater depth. On the other hand, the rock in the dam foundation is tightly jointed and impermeability was verified by low grout takes.

Seven major sub vertically dipping brittle ductile tectonic dislocations or faults, slickenside striated running in the northeast-southwest direction, were encountered in the dam site excavations. The width of these strike slip faults varies from 1 m to 5 m as encountered. All major faults were associated with slickenside closely to moderately spaced joints. Faults were observed to grow thick and thin in fracture intensity to branch out like veins of a leaf running sub parallel to the main fault direction (Perera 1993).

3.3.5 Rock structure and the quality

The dam is located on the north-eastern limb of the Balangoda syncline. The foliation of the rock on left bank has a south western dip of 30° – 35°. On the right bank the foliation dips at an angle 35° - 45° towards south-west. In the river channel the rock has a foliation dip of 5°-10°. The variation of the foliation dip is due to a folding of lower order. The most prominent joint set in the dam site area has a dip of 50° towards north. Two sub-vertical joint sets striking at 20° and 335° are also common.

A number of steeply dipping tectonic dislocations is present at the dam site. The thickness of the crushed rock within the zones of these dislocations does not exceed 3-5 m except in rare cases where the thickness reaches 10 m.

The rock mass quality has been categorized according to the following three groups.

- Group A: slightly weathered to fresh rock with high core recovery (> 90%), high RQD (>75%) and high seismic velocities (>3500 m/sec).

- Grade B: Moderately to slightly weathered rock with good core recovery (>25%), RQD (<75%), and moderately to high seismic velocities (2000 – 3500 m/sec).
- Grade C: Highly to completely weathered rock and residual soils with core recovery generally less than 25% and often zero and seismic velocities < 2000 m/sec.

The rock mass classification is based on a system which is modified and specially adopted for the Samanalawewa project geological classifications.

This rock mass quality classification system has been applied to the ground conditions at the dam site to provide a basis for describing the engineering geological conditions at the site as follows.

<u>Left Bank:</u>

The foliation is sub parallel to the valley slope which is covered with a mantle of grade C rock varying in thickness from zero at the river bed to 10-15 m at the top of the slope. Grade B rock occurs below the mantle of the Grade C as a layer (5-20 m thick), and also as isolated lenses at depth within grade A rock. The boundaries between different grades are generally gradational and irregular.

<u>Right Bank:</u>

The foliation dips steeply in to the hill side and weathering has penetrated deeply along bands of limestone and granulites. The thicknesses of Grade B & C are therefore much greatr on the right bank than on the left bank.

The mantle of grade C rock on surface varies in thickness from zero at river bed to about 50 m at the top of the slope. Bands of Grade C material extends in to the rock mass parallel to the foliations to depths up to 100 m below ground level. Such weathered bands are up to 5 m thick and have resulted in a very irregular contact with the underlying Grade B rock. The Grade B occurs as a continuous layer beneath the Grade C rock and as deeply penetrating bands parallel to the foliation. Many of these bands extend in to the hill side to levels well below river level and would thus be penetrated by any tunnel driven through the right bank.

Beneath the lower slopes the fresh to slightly weathered Grade A rock is found in isolated areas at depths of about 20 m but such areas tend to be separated by penetrating bands of

Grades B and C rock. Beneath the higher slopes the weathering typically penetrates to depths of more than 70 m, frequently below the river level.

River bed:

Grade C material is generally absent in river bed area and depths to Grade A rock formation is small, being less than 10 m.

3.3.6 Weathering

The tropical weathering of the metamorphic rock has resulted in formation of a crust of weathering, the thickness of which is negligible at the river bed and thickness increases towards the upper elevations of the banks.

In the dam foundation the surface of the gorge slopes are composed of talus and alluvial deposits having a maximum total thickness about 15 m. These deposits are characterized by low shear strength and high permeability. The river channel section is composed of slightly jointed hard rock. In the upper part of the river bank the thickness of the highly weathered rock reaches 24-25 m.

Weathering of the bed rock in Samanalawewa dam site consists of an ordinary weathering by air and water from the ground surface and a deterioration of rock through hydrothermal effect from underground. The hydrothermal influence does not only weaken the rock by altering the component minerals, but also prepares conditions for easy development of the weathering from atmospheric agents.

Weathering is exceptionally deep under the right bank ridge off the right abutment of the dam, especially in the granulitic gneiss bed. The bed rock of this part is distorted and sheared by faults, through which hydrothermal alteration has developed in to the bed rock (Perera 1993).

Tropical weathering forms a deep weathering profile in the right bank. The depth of weathering depends on the composition and degree of fissuring of bed rock. Along faults in rocks more susceptible to weathering, the penetration of weathering reaches 100 m. Weathering has penetrated to a greatr depth on the right bank where the strata dips in to the hill side. This deep weathering is common along the bands of limestone and granulites. The limestones within the zone of weathering are subjected to karstification. The limestones of the upper carbonate bearing bench on the right bank are karstified to a greater extent. Hollow solution cavities as well as partially in filled solution cavities are present in this zone.

In the weathering profile the following sequence of layers has been identified.

1. Residual soil
2. Completely weathered rock
3. Highly weathered rock
4. Moderately weathered rock
5. Slightly weathered rock
6. Fresh rock

The above items 2 to 6 commonly referred as the bed rock. Residual soil/weathered rock mantle covers the most of the project area. Fresh rock is exposed along the river channels and high ridges.

Layers in the weathering profile have been grouped in to three zones.

Zone (i)	Residual soil
	Completely weathered rock
	Highly weathered rock
Zone (ii)	Moderately weathered rock
	(Blocky mass. Blocks are fresh, joints are weathered and volume of weathered material 10 to 15 % of total massif volume).
Zone (iii)	Slightly weathered rock
	(Fresh rock. Joints are stained or slightly weathered).

Thickness of weathered zones (i) and (ii) reaches 30-40 m. thickness of slightly weathered zone (iii) does not exceed 2-3 m to 30-40 m in areas free of joints. Within faults zone (iii) extends to depths of up to 100 m or more.

Crystalline limestone bands occurring in the gneisses and granulites have undergone karst weathering. The base of karstification is the local base level of erosion (i.e. level of the Walawe river). At a greater depth the karst process has developed in the zones of tectonic disturbances drained by remote erosion paths. The dimensions of the solution cavities formed by karstification depend on the thickness of the limestone bands. Cavities with a volume of several thousand cubic meters are found in thick crystalline limestone bands. The form of these cavities varies from more or less equidimensional caverns to long narrow solution channels extending along the discontinuities. Some of the caverns are filled completely or partially with sandy clay or fragments of rock. During the excavation of the right abutment six large caves were detected. They were lying just upstream of the dam axis and one of them lying almost at the river bed level (375 m amsl). The Figure 3.4 shows one of those caves. These cavities were sealed with concrete during dam construction.

3.4 Hydrogeology

3.4.1 Ground water level monitoring

During the investigations, the ground water level was monitored in 38 observation wells (during 1976-1977) and in 31 observation wells during 1986-1987 periods. Since then to date the ground water level at site, especially of the right bank has been monitored continuously. In this regard a large number of observation wells and piezometers have been installed at site for the purpose of ground water level monitoring.

Ground water encountered in the right bank is associated with two rock, soil complexes.

- Weathered mantle, talus mantle and alluvium deposits occurring over almost the entire area as a blanket over fresh rock bed rock.
- Metamorphic bed rocks. Particularly karstified zones and deeply weathered zones along faults.

The ground waters of both complexes are hydraulically interconnected forming a single ground water horizon resting on fresh intact or slightly fissured rock basement. Along deeply weathered fault zones ground water may penetrate as deep as 200-300 m. Ground water in the karst limestone and fault zones is of confined nature and artesian flows have been observed. The direction of ground water movement is generally controlled by the ground relief but within the 2^{nd} complex the movement of ground water is affected by the structure of the fault zones and karst features.

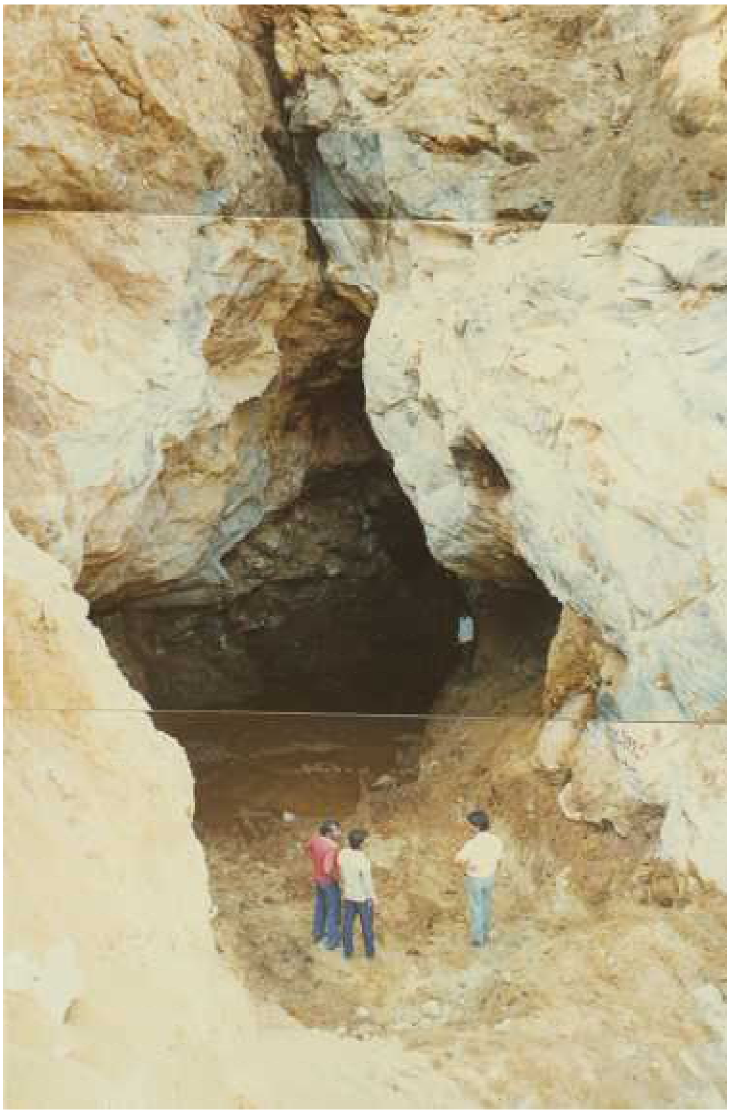


Figure 3.4 One of the Karstic caves found during excavations, in the right abutment

A number of low yielding springs issuing water from steep ground slopes have been noted at dam site. The majority of these springs are of seasonal nature and dries out during dry seasons. The fresh intact rock is either impermeable or of very low permeability. However, quartzites are permeable even in their fresh state due to a high degree of fissuring. The permeability coefficient of quartzite is 2-3 m/day. The highest permeabilities were encountered in crushed zones along faults causing water loss amounting to 70-80 l/min, during drilling.

Permeability tests indicate that in the weathered zones (i) and (iii) permeability ranges from 0.01 to 16 m/day.

Chemical analysis indicates that the ground water is of hydro carbonate nature. The mineral salt content is 0.02 – 0.67 g/lit. Ground water of low mineral content is associated with the 1st complex. The water is soft and classified as fresh/ultra fresh.

On the left bank the ground water table occurs parallel to and 10-15 m below the ground surface. From the fact that the crust of weathering is limited by a similar profile it can be deduced that the ground water flow is confined to the permeable weathered zone.

On the right bank, away from the river channel, the depth to the ground water table is as deep as 50m. With the presence of foliation dip towards the hillside, and high permeable layers of rock, it is more likely that some under drainage takes place. The occurrence of low ground water level and the observed drill water losses during core drilling may possibly be due to this under drainage.

3.4.2 Rock permeability

Permeability determines the capacity of a medium to allow for water passage. Materials can be grouped as being impervious or pervious according to the degree of water tightness they can withhold. Completely weathered rock or soils having a coefficient of permeability less than 10^{-4} cm/sec are considered as impervious.

Permeability testing was carried out to some extent during all the investigations since 1958. According to Gunaratne (1990), the most reliable data is available from the work done by Nippon Koei in 1986-1987. The data were plotted according to the location and the weathering grades.

The permeability test results show that the preserved bed rock is practically impermeable or having a very low permeability. The high permeability is characteristic for the crust of weathering, highly fractured slightly weathered bedrock and the zone of slickend rock along tectonic dislocations.

The results obtained revealed that, tentatively the majority of the original river bed within the survey area appears to be rock at or near the surface and it is steeply dipping beneath the left bank. Further to that, a very minor bed rock depression at up stream 100 m of the area was identified.

Chapter 4

Hydrogeological observations

4.1 General

The main objective of this study is to understand and establishment of the reservoir leakage mechanism. Therefore, studying the site hydrogeological behaviour will be of prime importance in evaluating the right bank characteristics with respect to the leakage phenomenon. Up to now the conducted studies and field investigations have failed to establish the reservoir leakage mechanism satisfactorily due to the inadequate knowledge on the hydrogeological characteristics of the site. Further this is the main reason the two major remedial exercises, i.e. grout curtain construction and earth blanket construction, could not seal the leakage and to reduce the associated high ground water levels in the right bank.

This chapter presents the observations made on the hydrogeological characteristics of the right bank with the objective of understanding the leakage mechanism.

4.2 Ground water level behaviour observations

In the dam and reservoir site a thorough hydrogeological assessment has been carried out since the early investigation periods, conducted several decades ago. In this regard mainly the permeability measurements and groundwater level observations through out the site have been made.

During early site investigations conducted in 1976-1977 period ground water level monitoring had been carried out using 38 observation wells installed in the dam site. Later in 1986-1987 another 31 observation wells were monitored. Along with the construction of the dam further set of groundwater level monitoring observation wells and standpipe piezometers were introduced.

The standpipe piezometers were used to monitor the groundwater level behaviour in the abutments and foundation of the dam and they have been installed inside the access and grouting adits. Later with the construction of the grout curtain in the right bank another set of standpipe piezometers were installed along the right bank. The purpose of these piezometers was to use them in assessing the water tightness effectiveness of the grout curtain.

The Table 4.1 gives a detailed account of all the ground water monitoring observation wells and standpipe piezometers used in the ground water level behaviour evaluation. The Figure 4.1 shows the locations where they are installed.

4.3 Ground water level behaviour before the reservoir impounding

The results of ground water level behaviour monitoring carried out during the construction stage showed that the ground water level in the right bank responded to the river water level changes. The data were collected from the monitoring observation wells close to the dam such as GW2 as well as to those far away from the dam such as GW18. According to the monitoring results most of the observation wells indicate a similar behaviour irrespective of the location. Further, as observed there the ground water level higher than the river water level suggest that before the impounding the right bank ground water regime is independent of any inflows from the river.

4.4 Ground water level behaviour during the initial impounding

On completion of the main construction works, reservoir impounding (initial impounding) on a trial basis was commenced in June 1991.

Table 4.1 Ground water level observation wells and piezometers used in the evaluation

Type	Identification	Installed location	Remarks
Observation wells	GW1,GW2,GW3,GW4,GW5, GW6, GW6A,GW7,GW8,GW9,GW10,GW11,GW12,GW13,GW14, GW15,GW16,GW16A,GW17, GW18	Right bank surface	
Observation wells	MS1,MS2,MS3	Right bank surface	
Observation wells	Y1,Z,	Right bank surface	
Standpipe piezometers	SP53 to SP 69	Right abutment access adit and grouting adits	
Standpipe piezometers	RBS1 to RBS31	Right bank grouting adits	

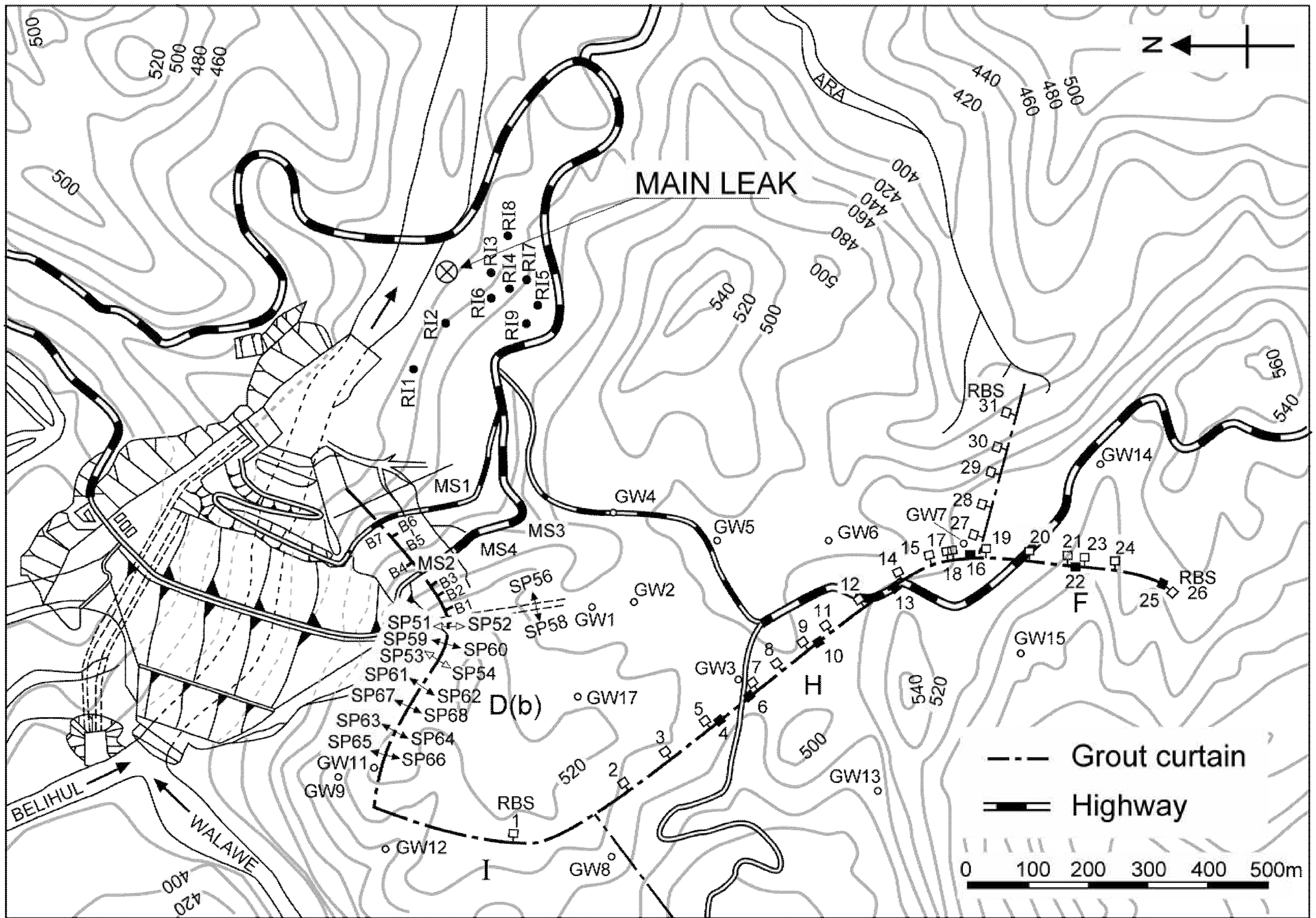


Figure 4.1 Location map of ground water level observation wells and piezometers

Idea of this exercise was to ascertain the water tightness of the reservoir which was of concern due to the weak geological conditions encountered during excavation works in the dam right abutment.

The impounding started on 2nd June 1991 and within two weeks the reservoir water level reached the 402.40 m amsl elevation. The Figure 4.2 shows the reservoir water level and the ground water level variation during this period. At this stage leakage appeared in the form of a small spring in the right bank about 300m down stream of the dam. Further the ground water level in the right bank too started to respond to the rising water level. On appearance of the leakage impounding had to be suspended as the reservoir water tightness could not be guaranteed and remedial measures were sought for.

4.5 Ground water level behaviour since second impounding (1992 to 1999)

4.5.1 During the second impounding up to the right bank burst incident

On completion of the reservoir remedial measures i.e. construction of the grout curtain in early 1992, reservoir impounding was commenced in March 1992. This was the first official impounding of the reservoir. The reservoir impounding was commenced by closing the bottom outlet of the dam. Further the reservoir filling was continued in a controlled fillingreat, allowing sufficient time for reservoir inner slopes and the dam core to get adjusted to the exerting water pressure.

With the impounding, reservoir water level gradually increased. At the same time the ground water level in the right bank too started to rise. This was indicated by the ground water monitoring observation wells and piezometers installed in the right bank. The right bank ground water level response was in such a way that it followed the reservoir level very closely. Thus when there was an increase in reservoir water level, the right bank indicated an equal amount of increase in ground water level within 10-15 hours.

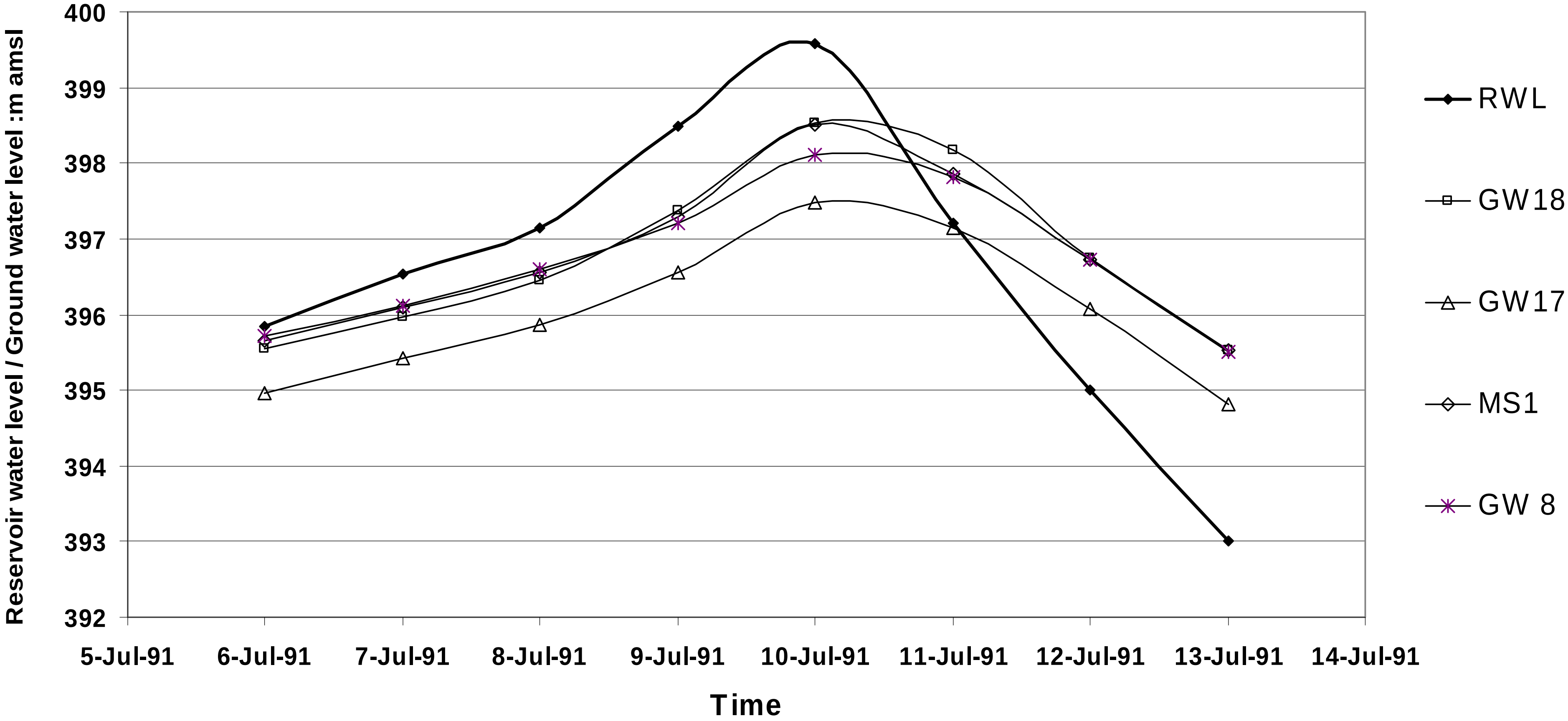


Figure 4.2 Right bank ground water level behaviour during initial impounding

Importantly this phenomenon was exhibited by majority of observation wells and stand pipe piezometers installed in the right bank.

During this period the reservoir leakage too reappeared as a small spring and developed with the rising reservoir water level. Initially the leakage flow rate was about 5 lit/sec but gradually increased to about 100 lit/sec just prior to the burst in the right bank.

Thus reservoir impounding continued notwithstanding the rising ground water level in the right bank and the rising leakage flow rate. However as the reservoir water level reaches almost 440 m amsl elevation, a sudden burst of the right bank near the leakage outlet occurred. This burst resulted in washing away of 25,000 m^3 of earth and rock material from the right bank.

This incident also followed by a sudden increase of the leakage flow rate to 7 m^3/sec, and then within 10-12 hours reduced to 2 m^3/sec. Later the leakage flow rate stabilized at 2 m^3/sec rate.

With the right bank burst incident the ground water level too reduced. The level dropped down by about 22 m suddenly and later increased slightly and stabilized at a level about 12 m below the reservoir water level. This ground water level dropping was exhibited by all the observation wells and standpipe piezometers which were earlier responding to the reservoir water level changes.

The right bank ground water level behaviour since second impounding up to the right bank burst incident exhibited by different monitoring observation wells and standpipe piezometers are presented in the following figures.

- Figure 4.3 - Ground water level variation over time of GW and MS series observation wells during second impounding
- Figure 4.4 - Ground water level variation over time of B and RI series observation wells during second impounding
- Figure 4.5 - Ground water level variation over time of RBS series standpipe piezometers during second impounding
- Figure 4.6 - Ground water level variation over time of SP series standpipe piezometers during second impounding

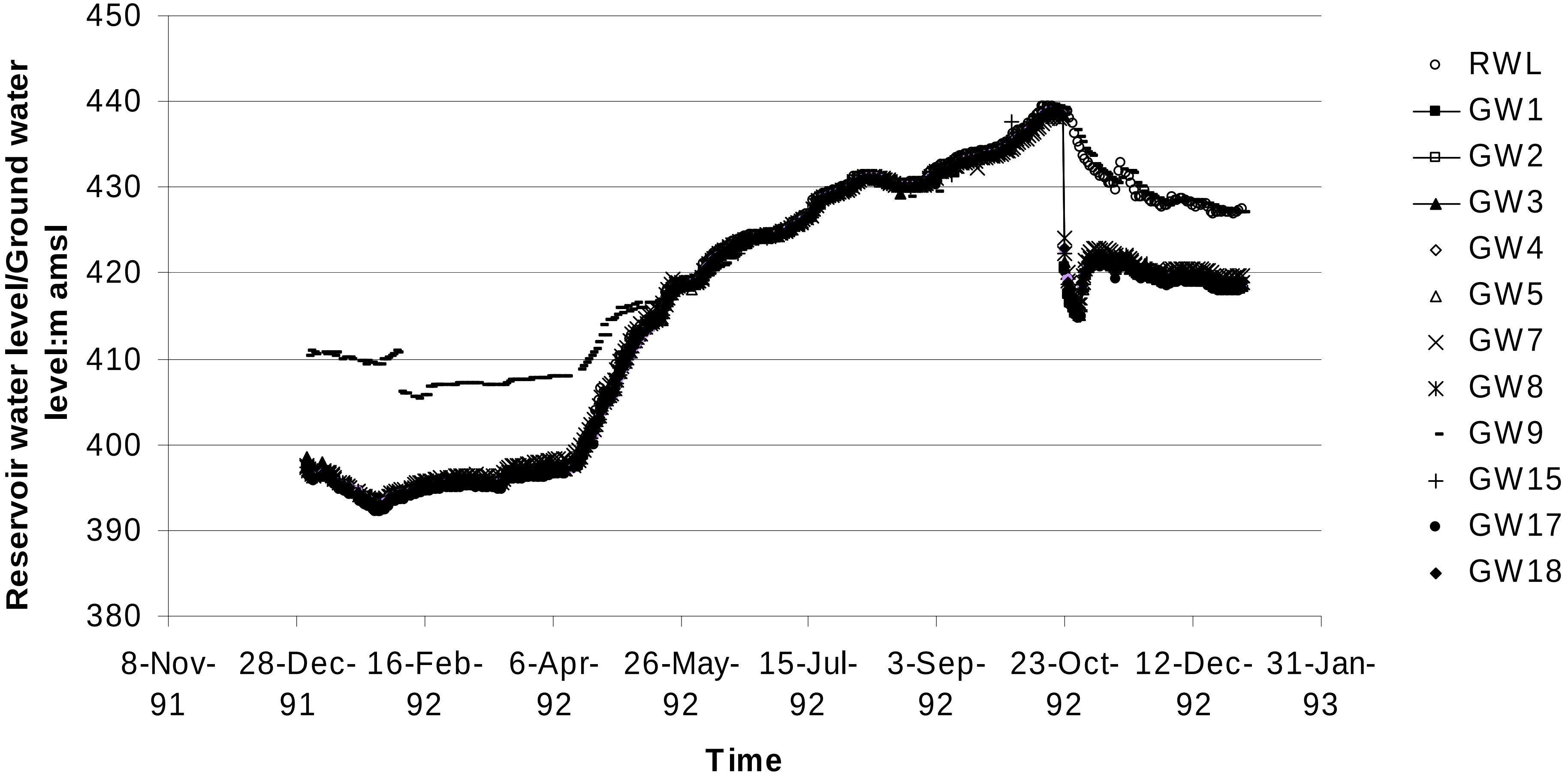


Figure 4.3 Right bank ground water level variation over time of GW and MS series observation wells during second impounding

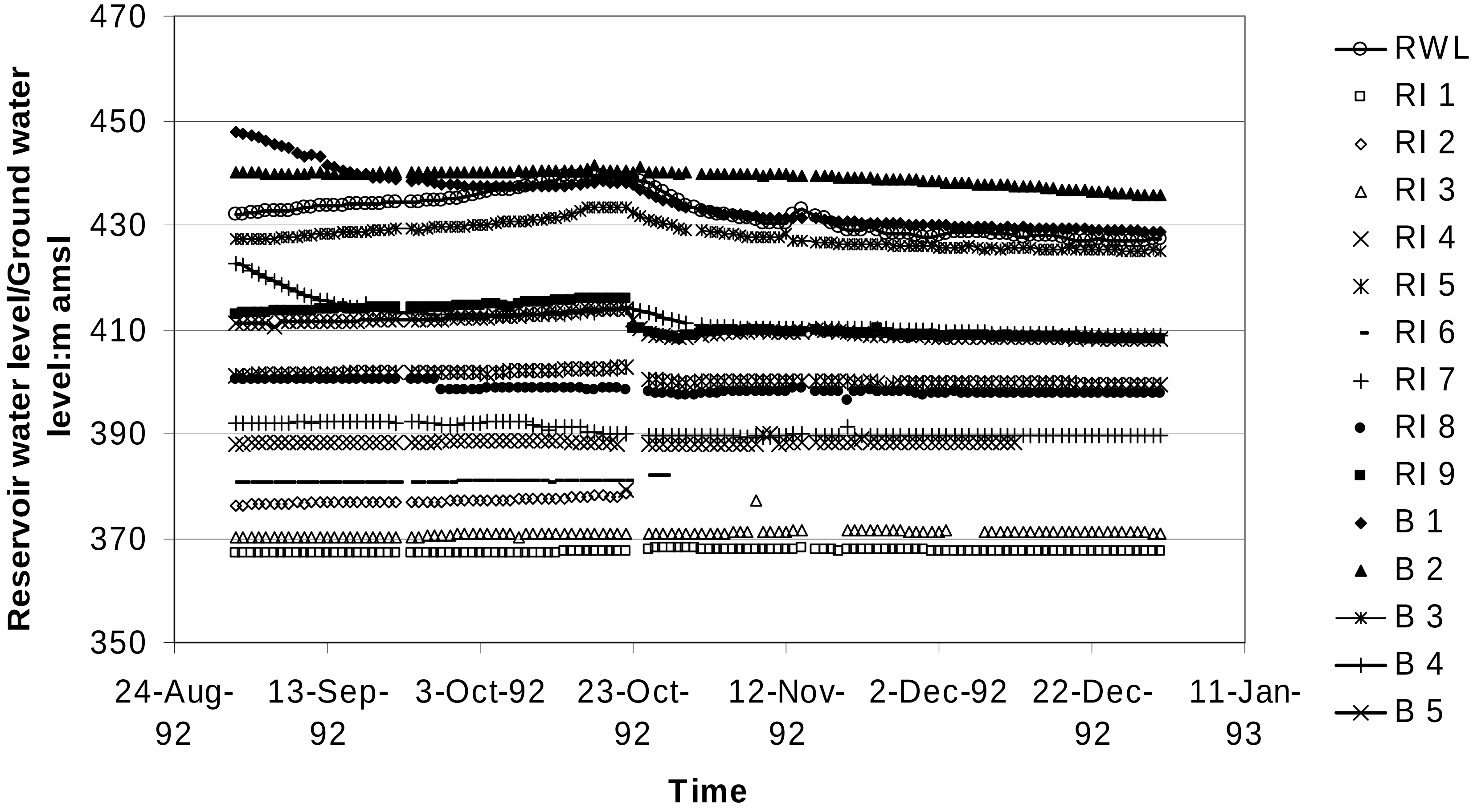


Figure 4.4 Right bank ground water level variation over time of RI and B series observation wells during second impounding

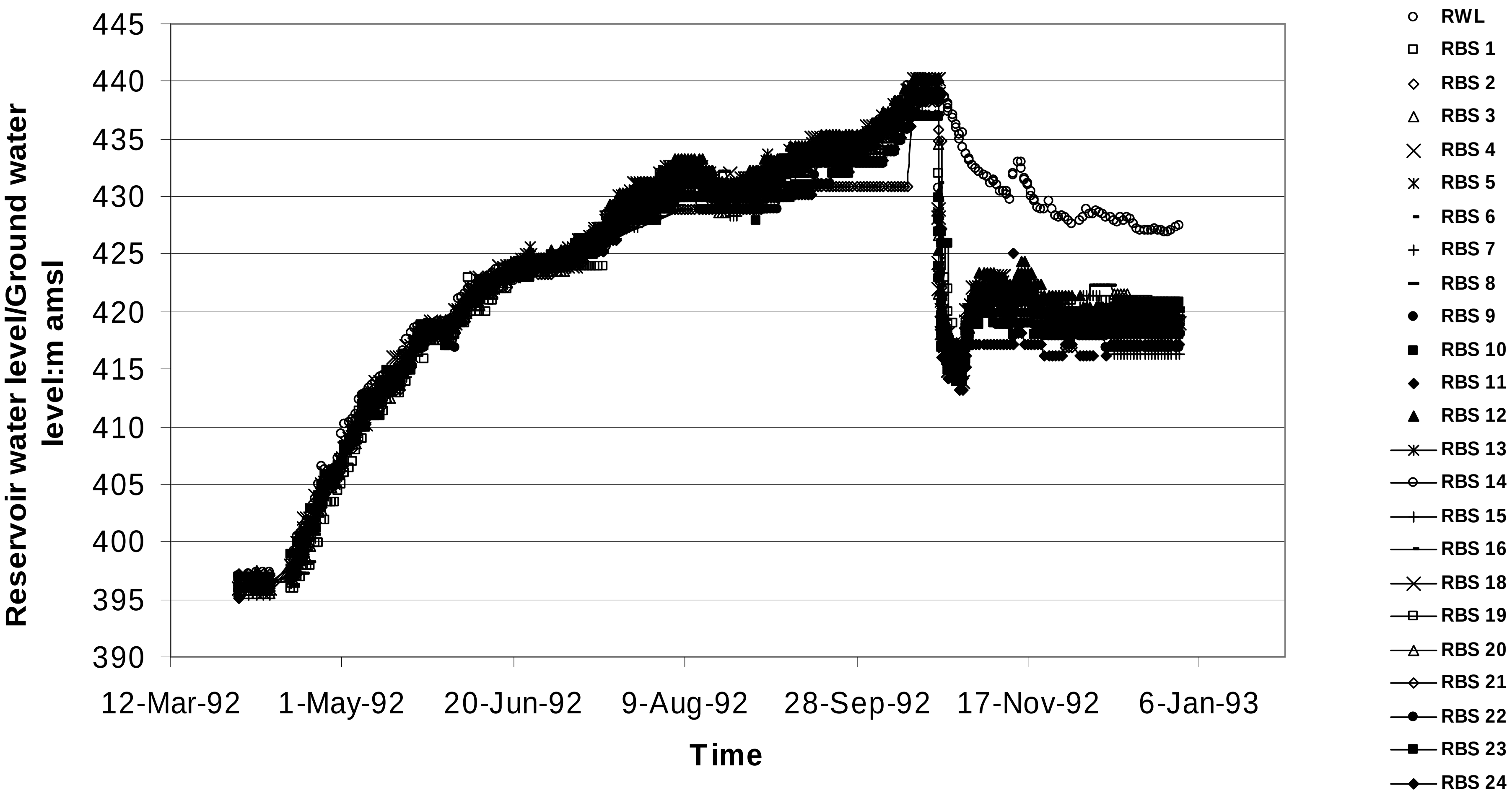


Figure 4.5 Right bank ground water level variation over time of RBS series piezometers during second impounding

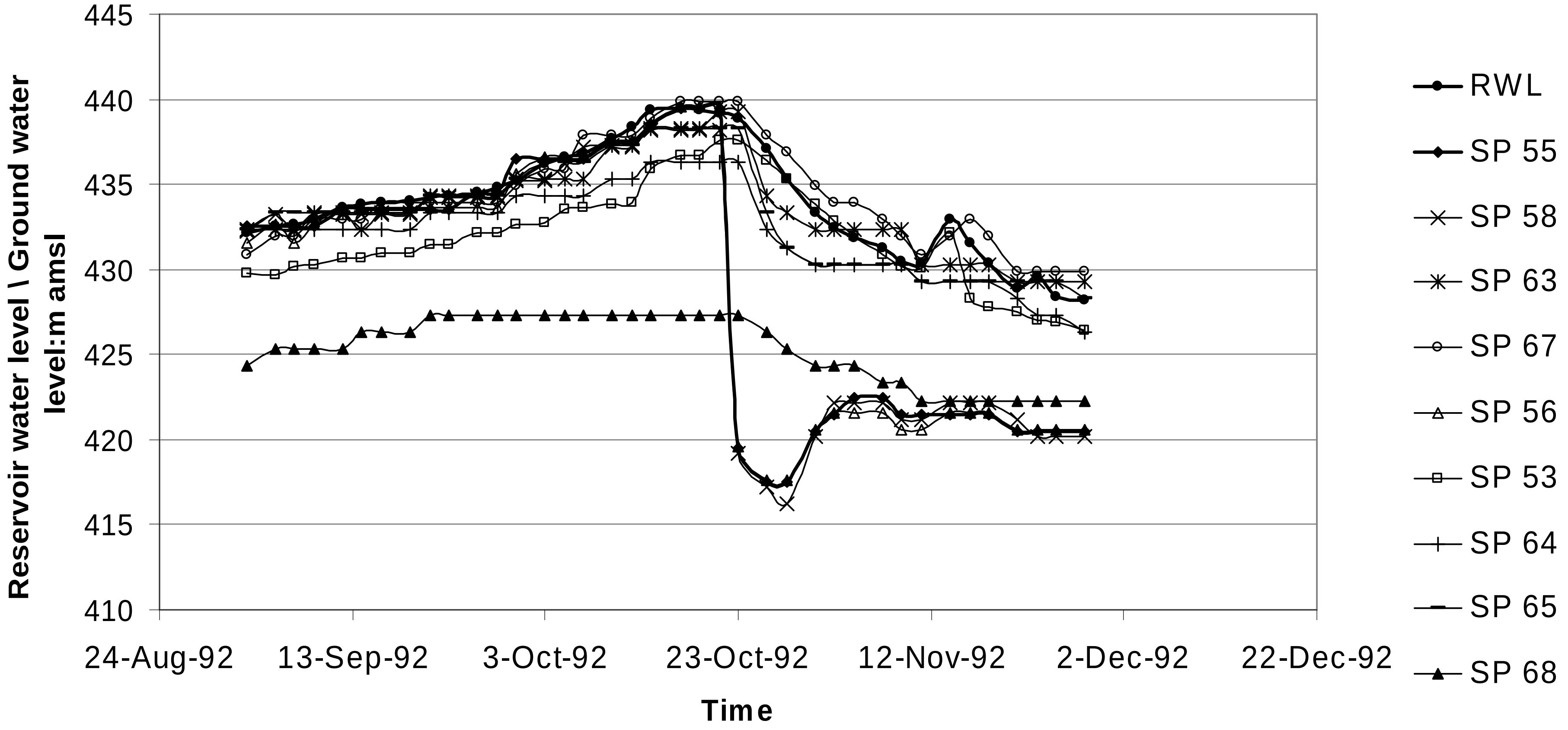


Figure 4.6 Right bank ground water level variation over time of SP series piezometers during second impounding

The above denoted GW, MS, RI and B observation wells and RBS piezometers are located on the right bank while the SP piezometers are on the dam right abutment. As observed in these figures except few observation wells and piezometers the majority of observation wells and piezometers located through out the right bank and in the abutment, behave in a very similar manner, indicating the porousness of the right bank . This will be discussed in detail later.

4.5.2 Post Burst behaviour (from 1993 to 1997)

After the right bank burst took place in October 1992 the reservoir water level lowered down and maintained at around 430 m amsl until the further leakage remedial measures are implemented. The main objective of maintaining the reservoir water level at a lower elevation was to reduce the ground water level in the right bank and hence to assure the stability of the right bank. With the pressure relief caused by the burst the right bank ground water level always stayed at a level approximately 10m below the reservoir water level. This was exhibited by the majority of observation wells and standpipe piezometers in the right bank through out the next five years to follow.

The observed ground water behaviour during this period is as shown in the following figures.

- Figure 4.7 - Ground water level variation over time of GW and MS series observation wells (from 1993 to 1997)
- Figure 4.8 - Ground water level variation over time of RBS series standpipe piezometers (from 1993 to 1997)
- Figure 4.9 - Ground water level variation over time of SP series standpipe piezometers (from 1993 to 1997)

As observed in the above graphs, majority of observation wells and piezometers exhibit a similar behaviour pattern with respect to the changes in the reservoir water level. The few observation wells and piezometers which were behaving independently indicate perched water table conditions. The Figure 4.10 shows the behaviour shown by them.

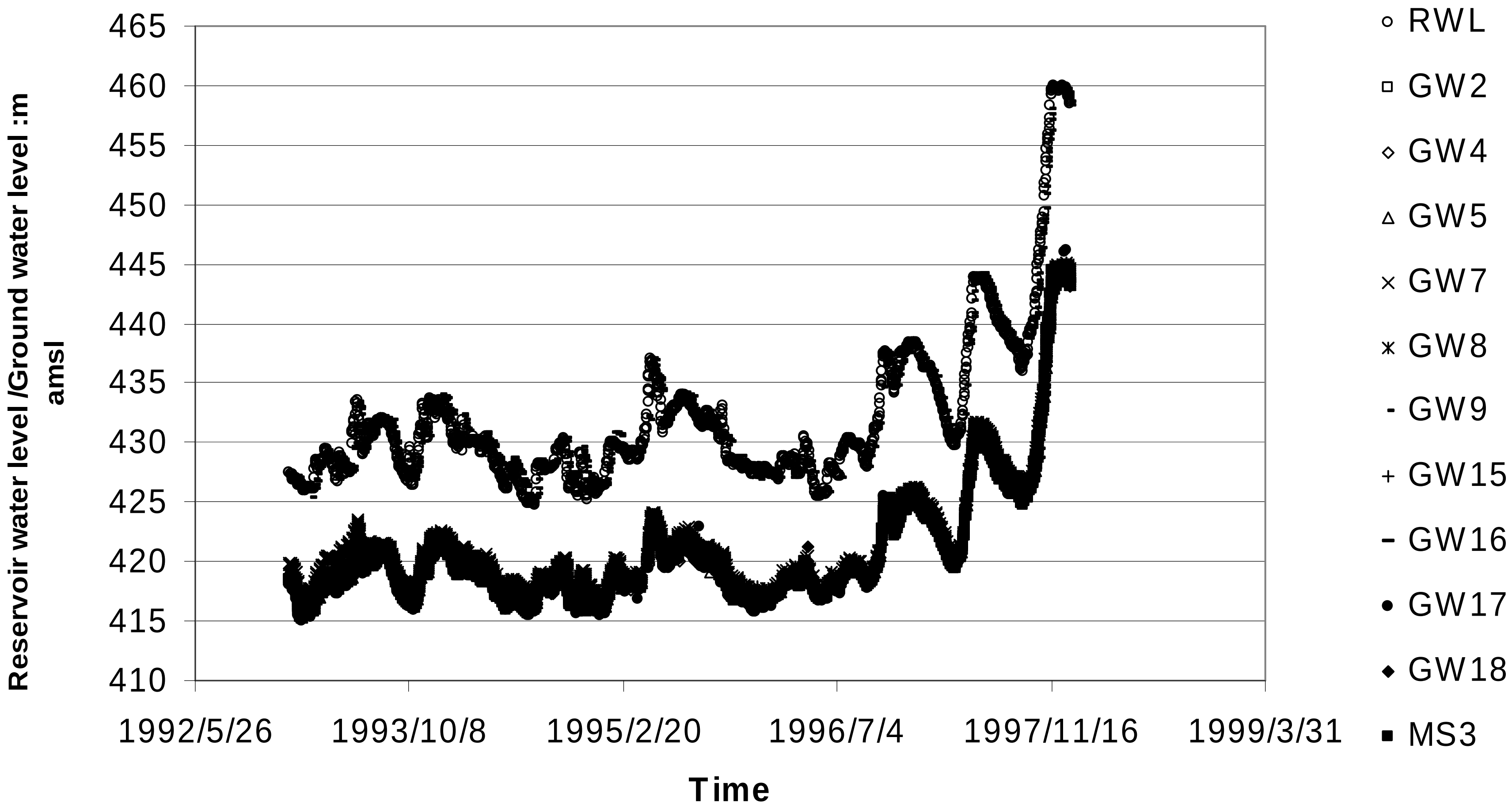


Figure 4.7 Right bank ground water level variation over time of GW and MS series observation wells during 1993-1997

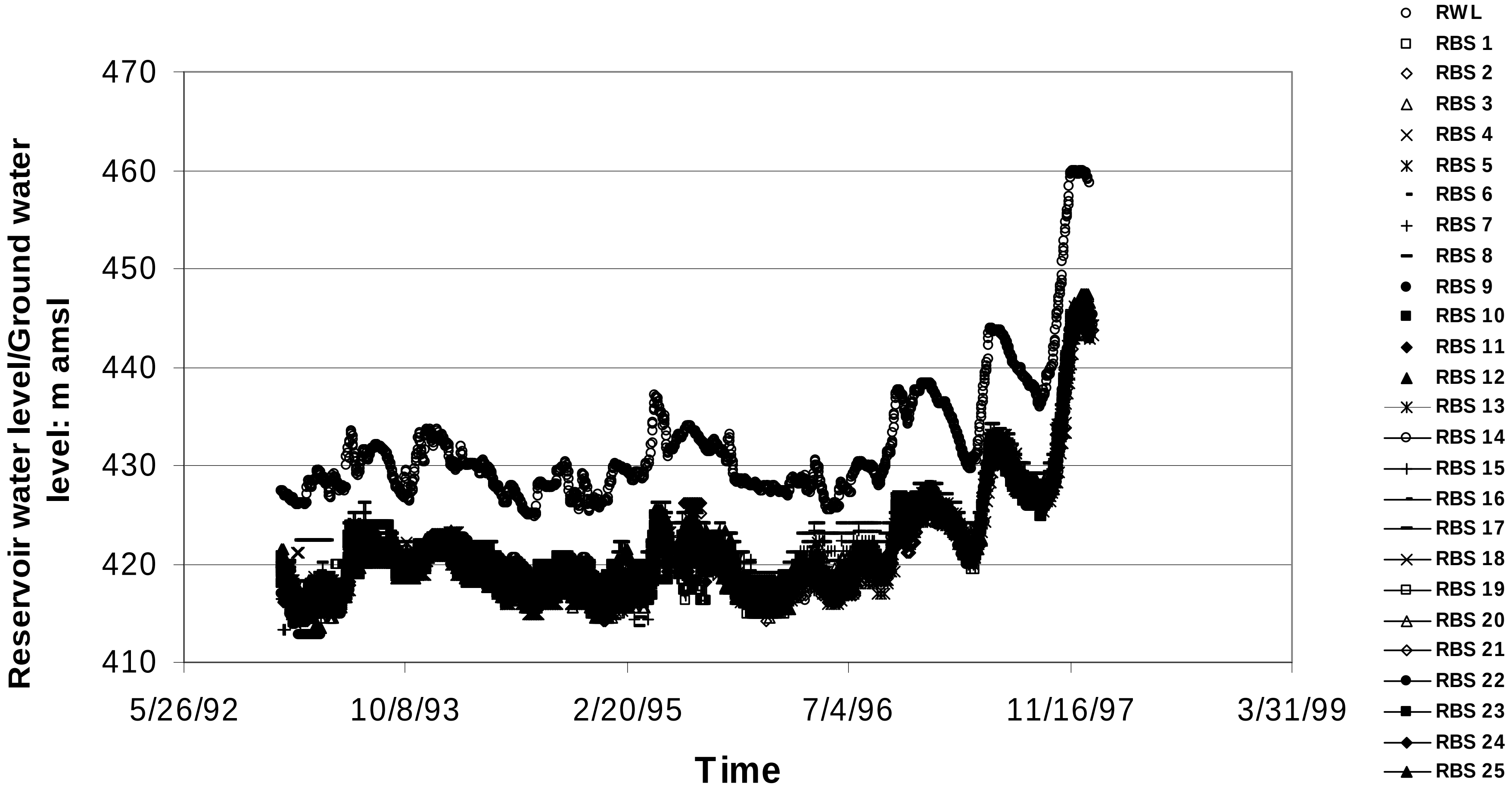


Figure 4.8 Right bank ground water level variation over time of RBS series piezometers during 1993-1997

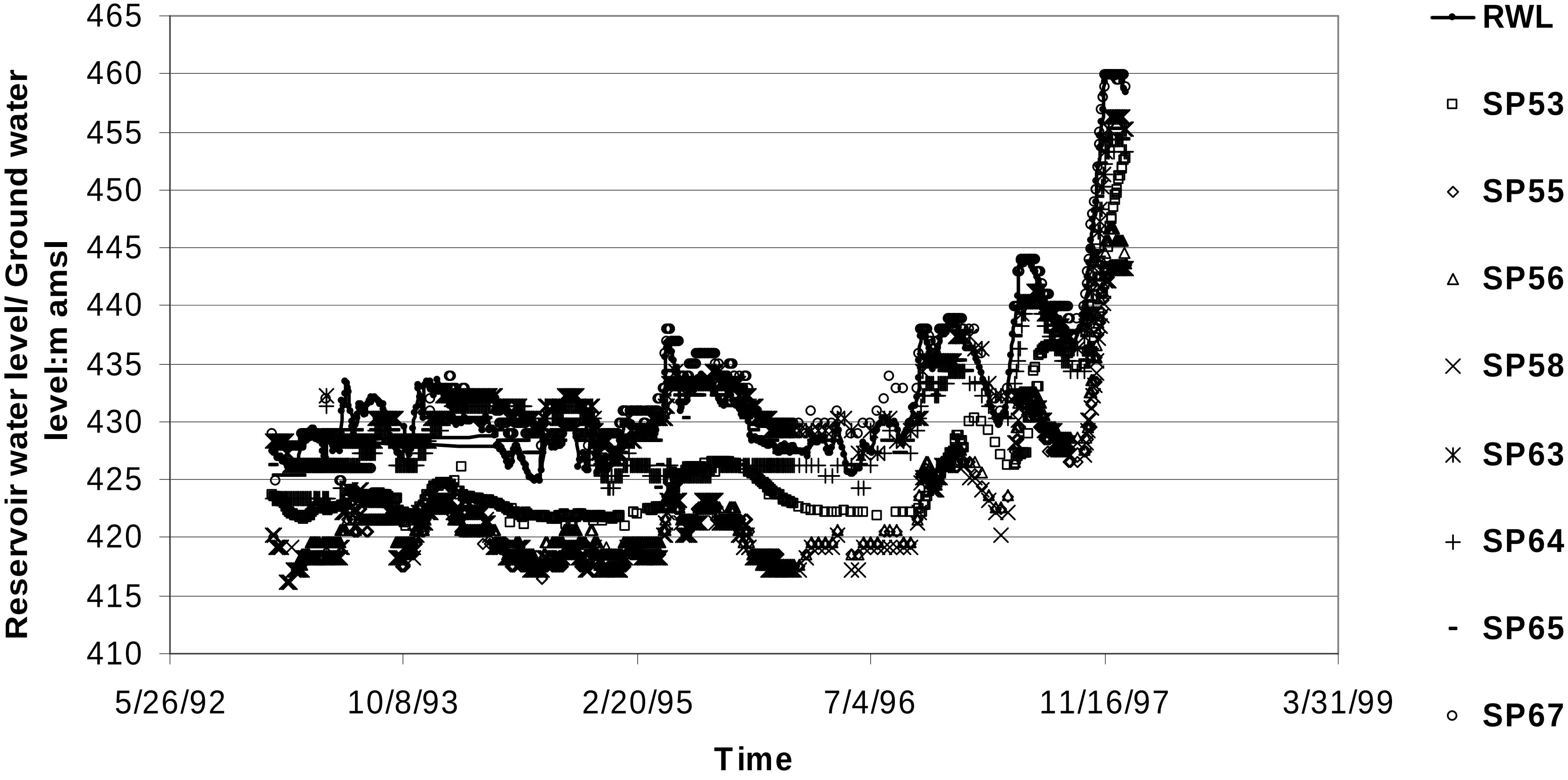


Figure 4.9 Right bank ground water level variation over time of SP series piezometers during 1993 - 1997

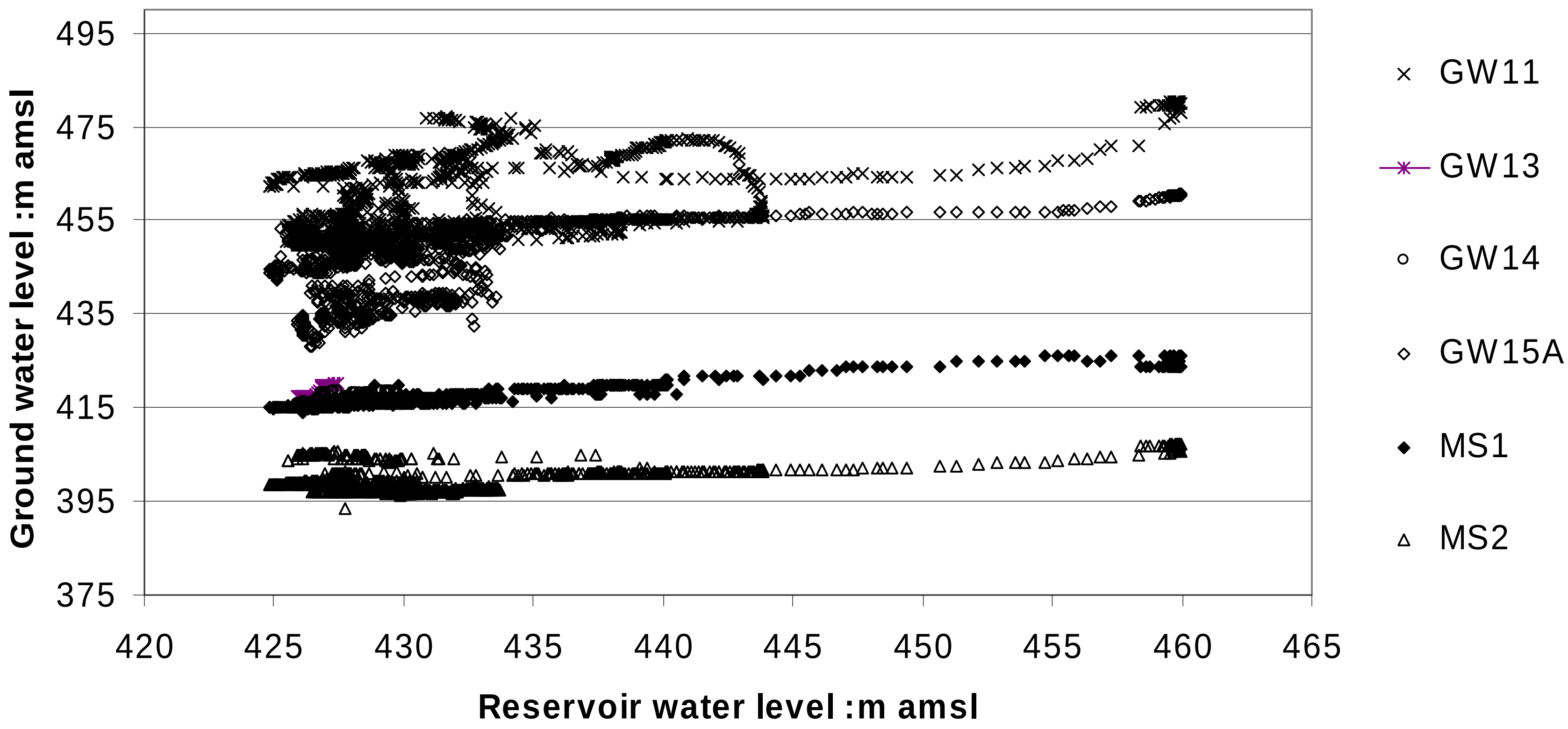


Figure 4.10 Ground water level – reservoir water behaviour of the observation wells which indicate perched water table conditions

It is also important to note that observation wells and piezometers near the dam as well as those located far away from the dam, behave in an exactly the same way irrespective of the installed location, thus indicating the perviousness of the right bank.
Further the ground water level behaviour during this period could be considered as a true hydrogeological representation of the right bank under stabilized conditions. After the water burst in October 1992, the right bank conditions got stabilized and no changes in its status were occurred until the earth blanket construction carried out during 1998. Therefore the ground water level behaviour during this period can be considered as a typical representation of the hydrogeological behaviour of the right bank after the full development of the leakage.

4.5.3 Ground water level behaviour during earth blanket construction

In March 1998 construction of the earth blanket was commenced as the second remedial measure exercise in sealing off the reservoir leakage. The details of the earth blanket process have been presented in the previous chapter. Under this exercise graded earth was dumped over the suspected ingress zones using bottom open type barges. However no response in leakage or ground water levels was observed during earth dumping within the suspected ingress zones. Later when earth dumping was carried out in an area out side the suspected ingress zones, the leakage and the right bank ground water level started to respond. When earth was dumping on a location identified as block ‘X’, about 500 m up stream of the dam, the right bank ground water level dropped abruptly by about 10 m and the leakage flow rate reduced by about 0.2 m^3/sec. This drop in the ground water level was exhibited by majority of the observation wells and standpipe piezometers installed in the right bank. This sudden drop in the right bank ground water level and the leakage rate was a positive sign of leakage getting reduced, indicating that a leakage inlet in the reservoir bed got sealed by the dumped earth material. It resulted in the reduction in the net ingress area causing right bank ground water level and the leakage rate to drop. However further earth dumping did not improve the situation and hence it suggested that there were no more leakage inlets lying in the same area.

The observed ground water level behaviour during earth dumping will be discussed in detail in a later section.

4.6 Ground water behaviour after earth blanket construction (from 1999 to 2005)

In the absence of further reductions in the leakage rate and the right bank ground water level, the earth blanket construction was concluded in early 1999. Since then to date no remedial measures were attempted and the reservoir was operated in a normal manner without any constraint on the level control. The leakage continued to flow at the same phase with slight changes according to reservoir level changes. The right bank ground water level too fluctuated with the varying reservoir water level while maintaining a difference of about 22m with the reservoir water level.

The right bank ground water level behaviour since 1999 to 2005 has been studied and is as shown in the following figures for different types of observation wells and standpipe piezometers.

- Figure 4.11 - Ground water level variation over time of GW and MS series observation wells (from 1999 to 2005)
- Figure 4.12- Ground water level variation over time of RBS series standpipe piezometers (from 1999 to 2005)
- Figure 4.13 - Ground water level variation over time of SP series standpipe piezometers (from 1999 to 2005)

As the above figures depict majority of the observation wells and standpipe piezometers follow a similar pattern. The variation of the right bank ground water level over time during the period 1999 to 2005 is similar to the behaviour observed before the earth blanket construction except the increase in gap with the reservoir water level.

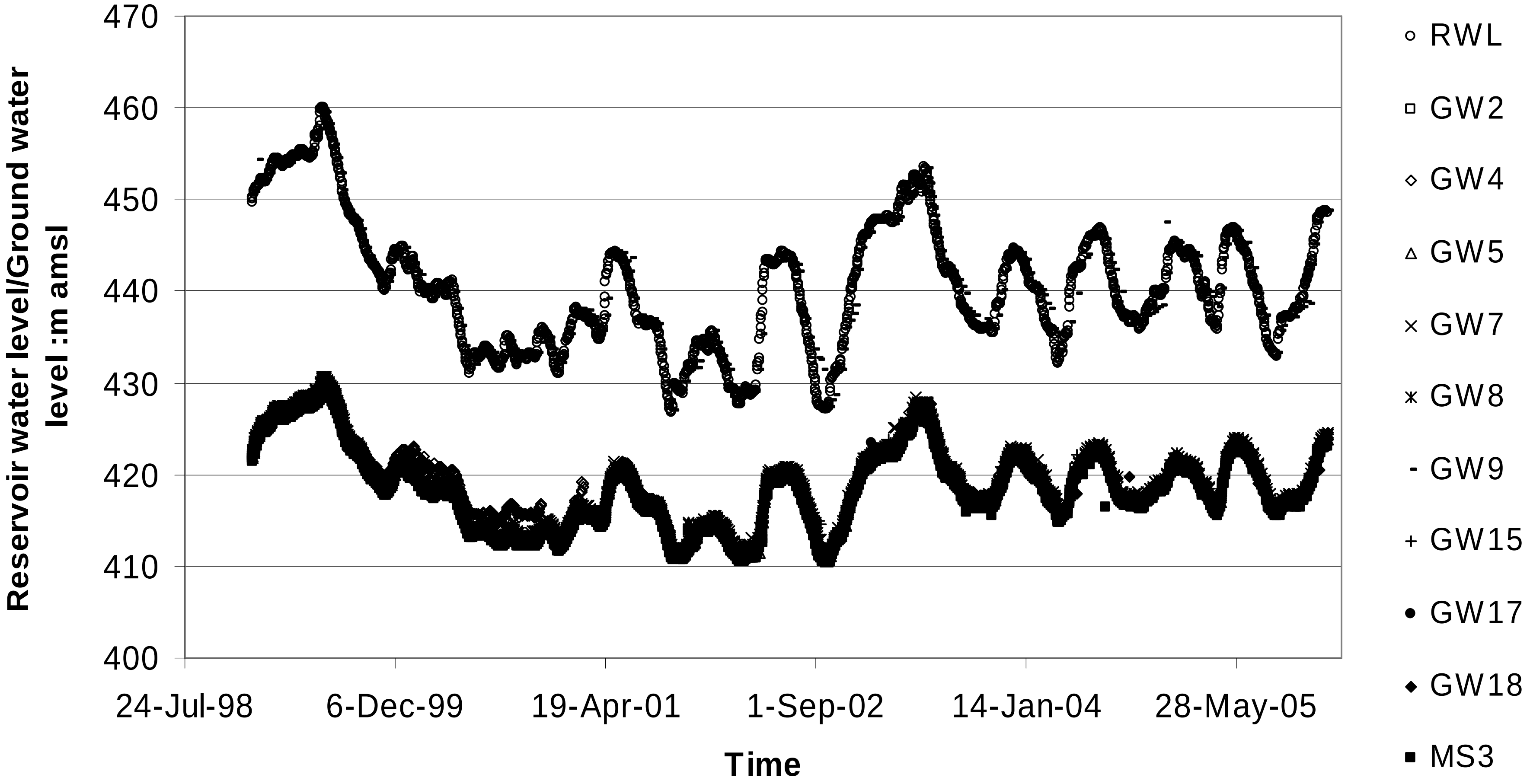


Figure 4.11 Right bank ground water level variation over time of GW and MS series observation wells during 1995-2005

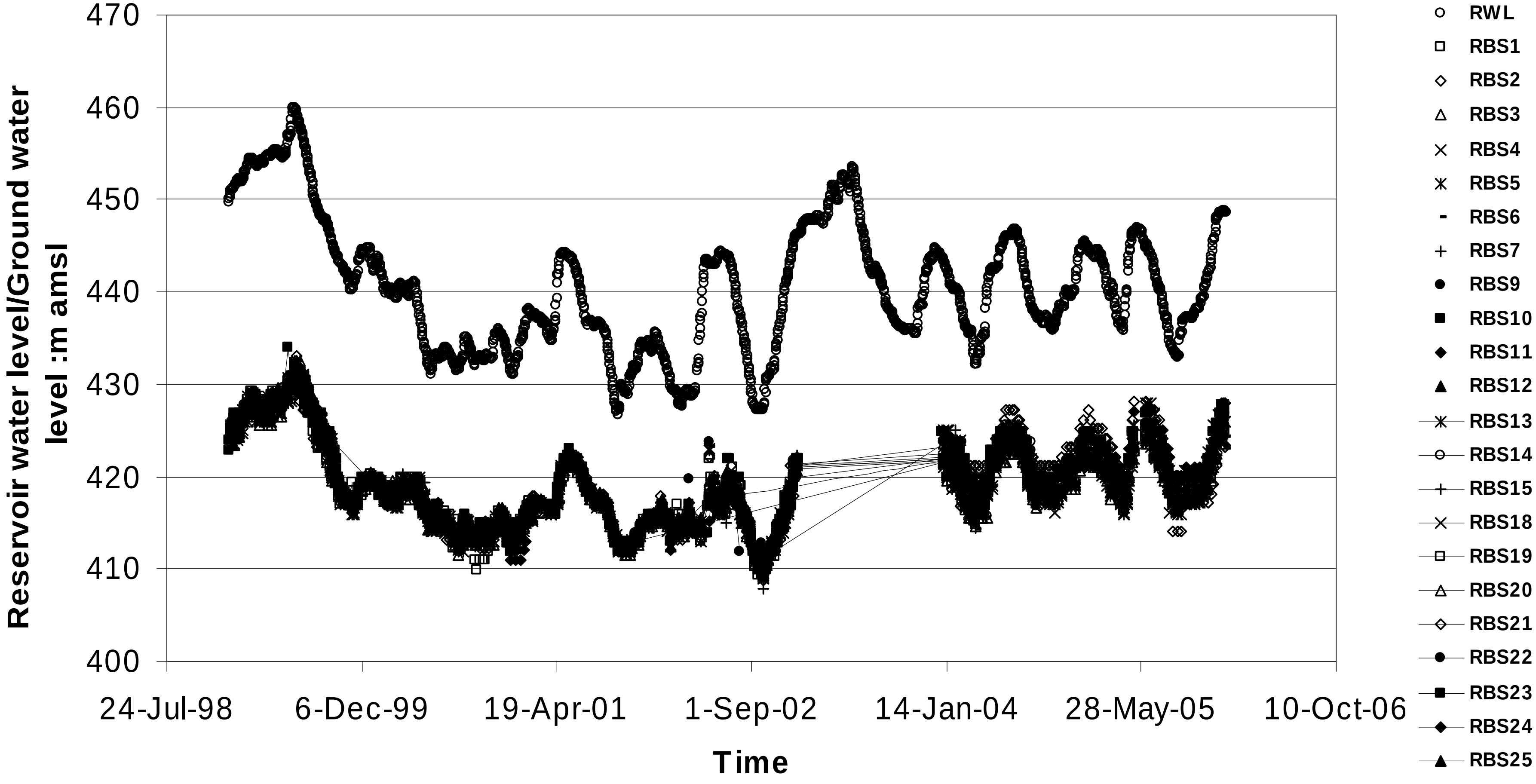


Figure 4.12 Right bank ground water level variation over time of RBS series piezometers during 1995 - 2005

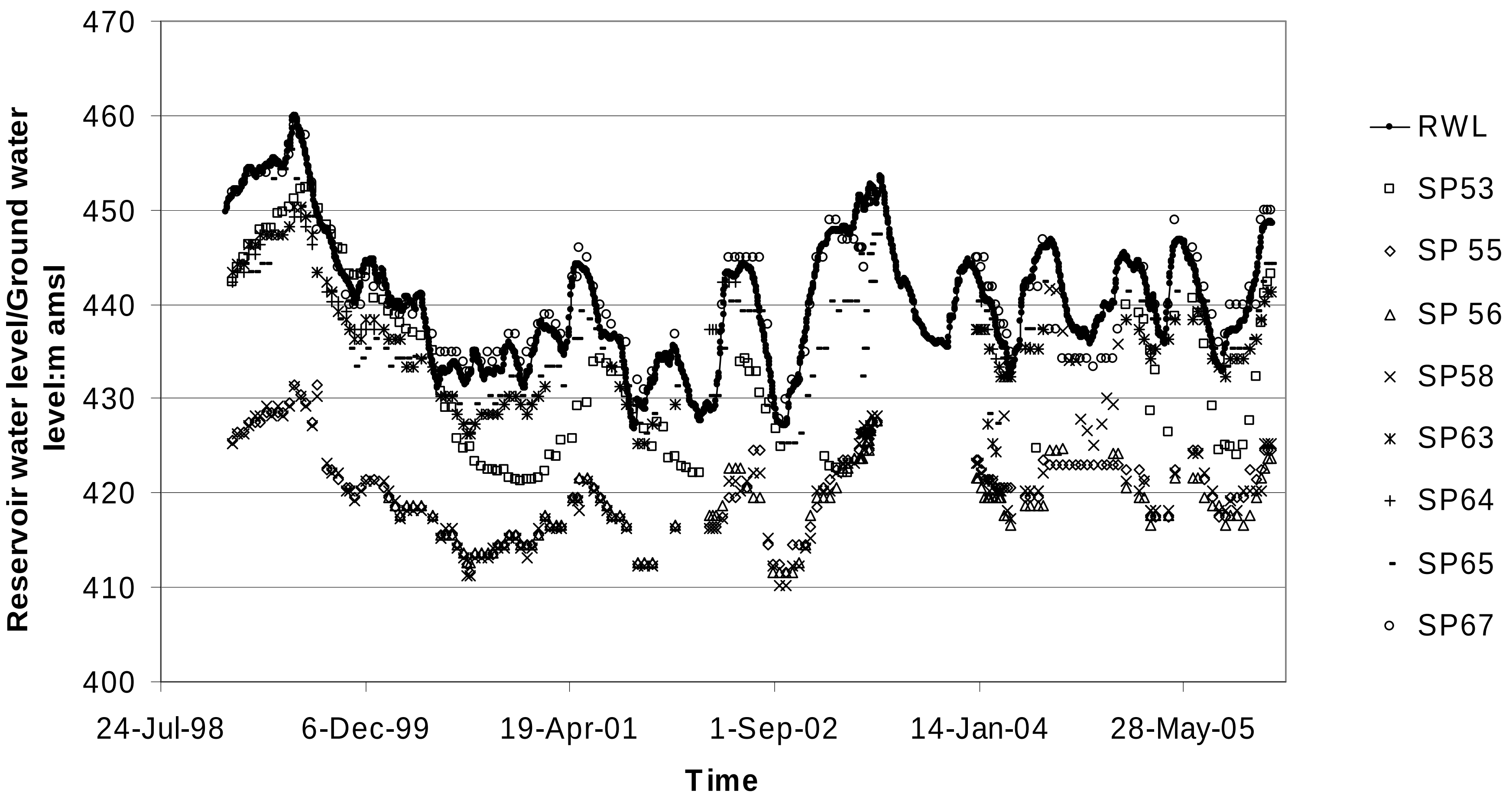


Figure 4.13 Right bank ground water level variation over time of SP series piezometers during 1995 - 2005

4.7 Hydrogeological behaviour based on water chemistry studies

Since 1990's, Water quality chemical analysis had been effectively used in the identification of possible leakage zones in the Samanalawewa reservoir. It was considered that the study of water chemistry by treating the reservoir water as a tracer is useful in tracing the groundwater movements within the right bank.

Water samples collected from the reservoir, leakage outlet, observation wells and piezometers in the left bank and right bank at more or less regular intervals have been analyzed for various chemical parameters. Mainly attempts were made to find a reasonable correlation among the variation of water quality and the leakage incident, which would help in identification of reservoir leakage paths.

Apart from the periodical chemical analysis, monitoring of samples obtained from sink holes, augur holes and observation wells recently drilled, as well as several other leakage locations were analyzed for different chemical parameters.

Since the beginning of the first trial impounding of the Samanalawewa reservoir, chemical parameters of water samples such as sodium (Na^{+1}), potassium (K^{+1}), calcium (Ca^{+2}) and sulphate (SO_4^{2-}) alkalinity were measured and plotted in STIFF diagrams. According to the distinctive shape of the diagram, each water sample could be described of their origin.

The results obtained from laboratory test were analyzed. The leakage water indicated sharp changes with respect to reservoir water. It indicates that leakage water is more dominated by deep ground water. Further, groundwater retained in grouting adits and reservoir water shows variation of chemical quality. This chemical quality difference has widely being used to identify the leakage paths. Results indicate that river water mixing take place through out the banks and also at some specific areas

Electrical Conductivity (EC) gives a general indication of dissolved ion concentration in water. Therefore a change in EC values suggests a change in ion concentration in water at particular location. Electrical conductivity and total hardness values of water samples collected since 1992 were measured continuously. Comparison of variation of electrical conductivity of water, between the shallow piezometers and deep piezometers was done in order to find a reliable correlation.

Efforts were made several times to detect the leakage paths through tracer tests using salt as the tracer. This has been carried out in the sink holes identified at a later stage on the upstream Walawe left bank area where the groundwater table was observed to be below the reservoir level. However, results were not successful most probably as the salt is getting diluted in a huge volume of water in the subsurface reservoir at the great depths of right bank and the bottom of the reservoir.

4.8 Isotope Studies

4.8.1 Application of Isotopes

Isotope techniques are widely used in seepage and leakage investigations associated with dam & reservoirs.

Leakage incidents associated with dams and reservoirs have been reported frequently from projects around the world. These leakage incidents could be associated either with the reservoir banks, dam foundations or in the dam body itself or may in a combination of them. The scale of a leakage could range from a small dripping coupled with wet patches to a stream flow with a flow rate of several cubic meters per second resulting an economic loss by reducing the expected benefits of the project. Additionally a leakage could pose stability and safety problems due to the saturated ground as a result of activated ground water regime in the surrounding areas fed by the leakage ingress zones. There are also cases where reservoirs have been abandoned due to inability to retain water.

In most of the cases main cause for a reservoir leakage is due to adverse geological conditions in the surrounding ground structure, which forms and holds a reservoir. Further the unsuitability of the ground may be either due to unforeseen geological conditions or underestimation of the imperviousness of the geological features resulting adoption of inadequate measures in improving the reservoir water tightness.

During the last four decades the use of isotopes, either naturally occurring (environmental) or intentionally injected (artificial isotopes) have proved their value in studies related to water resources assessments, management and development in general and specially in leakage and seepage investigations associated with reservoirs. In addition to the applications in leakage and seepage studies, isotope techniques are used in the following areas too.

- Source of recharge and estimation of recharge to ground water
- Source of ground water salinity and pollution
- Surface water- ground water salinity and interconnection
- Aquifer- aquifer interconnection
- Dating of ground water
- Efficacy of artificial recharge
- Dynamics and sedimentation in lakes and reservoirs

Before getting in to details it is worthwhile to give an introduction to the fundamentals on isotopes. An atom consists of a nucleus surrounded by electrons. Most of the mass of the atom is concentrated in the nucleus, which is formed by two kinds of particles: neutrons and protons. Protons are positively charged while neutrons carry no electric charge and hence behave neutrally. The number of protons is characteristic for each chemical element and is called the atomic number (Z). This number is equal to the number of electrons, which are negatively charged, so that the atom as a whole is neutral. Due to the repulsive electrical forces exist between protons, the presence of neutrons is required to stabilise the nucleus. In the case of light elements, the number of protons and neutrons is equal. The sum of protons and neutrons is called the mass number (A).

The term nuclide refers to each combination of neutrons and protons that can compose each element. The atomic nuclei containing different numbers of neutrons and protons are called Isotopes. All isotopes of a given element present the same chemical behaviour because the chemical properties are controlled by the external configuration of the electrons, which is the same for all isotopes of a given element. In nature, each element is constituted of a mixture of different isotopes. However, the tiny differences of mass of the atoms or molecules containing other isotopes besides the most abundant ones are responsible for a different physical behaviour, in which the structure and the characteristics of the nucleus are relevant. Isotopes are usually represented in the form AX, where X denotes the symbol of the element.

The environmental isotopes are those, which occur in the environment in varying concentrations, and over which man has no direct control. Generally the environmental isotopes are classified in to two categories:

Stable isotopes

Radioactive isotopes

Stable isotopes are those that are commonly found in natural elements. Some elements contain only one stable isotope. However, when several stable isotopes are present in the natural element, their relative proportions remain constant, although small differences can originate when element is involved in chemical reactions or phase changes.

The stable isotopes, which are commonly used in this type of studies, are

Deuterium (^{2}H)

Oxygen - 18 (^{18}O)

Carbon - 13 (^{13}C)

Sulphur - 34 (^{34}S)

Radioactive isotopes are those undergo spontaneous radioactive decay. That occurs mainly in the isotopes showing a large shortage or excess of neutrons compared with the stable isotopes of the same element. Details radioactive isotopes are not discussed here.

Most commonly used radioactive isotopes in this type of studies are

Tritium - (^{3}H)

Carbon - 14 (^{14}C)

The three heavy isotopes of hydrogen and oxygen mentioned above viz. Oxygen - 18 (^{18}O), Tritium (^{3}H), Deuterium (^{2}H) constitute an integral part of the water molecule, in the form of HDO, $H_2{}^{18}O$ and THO. Water molecules containing any of the heavy isotopes mentioned above, behave from the chemical point of view, as any other molecule formed exclusively with the most abundant isotope ($H_2{}^{16}O$). Therefore their behaviour is almost ideal when compared with other tracers whose properties might be or certainly are different when compared to those of water molecules. Water molecules containing these heavy isotopes are perfect tracers to study the mixing and behaviour characteristics of different water bodies in the water cycle.

4.8.2 Stable isotopes of Water

Natural hydrogen is exclusively formed by two stable isotopes ^{1}H(99.985%) and ^{2}H or Deuterium (D)(0.0155). Similarly Oxygen is formed of three isotopes, ^{16}O(99.759), ^{17}O(0.0374) and ^{18}O(0.2039). ^{1}H and ^{16}O are the most abundant species, and the usual form to express the composition of water is $^{1}H_2{}^{16}O$. Out of the nine other isotopically different water molecules that can be formed with the indicated isotopes, only three viz. $^{1}H_2{}^{16}O$, $^{1}HD^{16}O$, and $^{1}H_2{}^{18}O$ occur in nature in easily measurable concentrations. Taking the Ocean as the major reservoir of water, and therefore representing the typical water molecule, respective abundance of the three most abundant molecules are

$^{1}H_2{}^{16}O$ 997.680 parts per million

$^{1}HD^{16}O$ .320 parts per million

$^{1}H_2{}^{18}O$ 2.000 parts per million

The Table 4.2 shows some of the stable isotopes of some light elements. The common form to express the abundance of a given isotope is by using isotopic abundance ratios(R), defined as follows. For instance $^{2}H/^{1}H$ or $^{18}O/^{16}O$. For practical reasons, instead of using the isotope ratio R, isotopic compositions are generally given as δ values, the relative deviations with respect to a standard value, as defined by:

$$\delta = \frac{R_{sample}}{R_{s\tan\ dard}} - 1$$

Table 4.2 Commonly found stable isotopes

Element	Z	N	A	Abundance	Symbol
Hydrogen	1	0	1	99.985	^{1}H
	1	1	2	0.0155	^{2}H; D
Carbon	6	6	12	98.892	^{12}C
	6	7	13	1.108	^{13}C
Nitrogen	7	7	14	99.635	^{14}N
	7	8	15	0.365	^{15}N
Oxygen	8	8	16	99.759	^{16}O
	8	9	17	0.037	^{17}O
	8	10	18	0.204	^{18}O
Sulphur	16	16	32	95	^{32}S
	16	17	33	0.75	^{33}S
	16	18	34	4.21	^{34}S
	16	20	36	0.02	^{36}S
Chlorine	17	18	35	~75.7	^{35}Cl

The accepted standard for the isotopes in water is VSMOW (Vienna Standard Mean Ocean Water).

Case study1

In the La Sierpe Hydropower project in Panama, water started to leak in to the powerhouse through the cavern roof and the source of it was unknown. Reservoir water to the power plant is conveyed through an underground pressure pipeline and it was suspected that the tunnel, which is few km long, could be feeding the leak. On the other hand a small creek, which was running close to the power plant could also have connected, and feeding the leak. Isotope analysis was carried out and it gave the following results.

- Leakage water in the power plant $\delta D = -72.5\%$, $\delta^{18}O = -10.65$
- La Sierpe reservoir $\delta D = -42.1\%$, $\delta^{18}O = -\ 6.76$
- Chiriquicito Creek $\delta D = -63.2\%$, $\delta^{18}O = -\ 9.19$

These results clearly showed that the leaks were not connected to the reservoir but to the nearby creek.

Further the continued measurements confirmed the above findings showing how the creek water isotopic composition varied with that of the leakage water.

The Isotope approach requires an adequate sampling programme in order to ascertain the all possible variations with time and space. The isotopic composition of a lake may be inhomogeneous if water bodies of different origin form the reservoir. If this is the case, only water from the section where losses occur should be suspected of having a relation with the ground water.

In this study only the applications of Isotope techniques in dam and reservoir leakage and seepage investigations are discussed.

As the initial phase of this study the environmental Isotopes were used as the tracer in understanding the leakage phenomenon. In this regard the natural isotopes present in the different water sources are monitored and the isotope signature is established. Later comparison of different signatures is done to identify hydraulic relationships that may exist among different water sources.

4.8.3 Isotope study at Samanalawewa

The first step of the study was to establish a proper sampling plan. In deciding on the sampling plan reservoir configuration and the site geological structure was taken in to consideration. This plan initially included about 20 locations representing the whole reservoir system. Thus the sampling plan included river water, leakage outlet, and ground water monitoring wells, drain pipes and rain water precipitating in to the reservoir area. The dam being located just down stream of the confluence point of Walawe river with its main tributary Belihul river, measurements were done for two rivers separately. All these locations were monitored on a regular basis for a period of about 12 months to establish the stable isotope signatures of the reservoir and the surrounding ground water system. The sampling locations can be found in the dam and reservoir layout plan provided in previous chapters.

The RBS2, RBS6, RBS13, RBS23 and SP58 are standpipe piezometers installed in the grouting adit in the right bank while GW2, GW11, GW18 and MS3 are surface ground water monitoring wells in the right bank. This grouting adit which is 1.8 km in length and driven in to the right bank at river bed level was used in constructing the 100 m deep grout curtain implemented as the first leakage remedial measure.

The monitoring well GW 18 which is located about 2.5 km away from the dam on the right bank is not shown in the figure. Which is the sampling point located furthest away from the dam. The monitoring well GW19 is located in the left bank.

Sampling of water from above locations was carried out on a monthly basis and the testing of them was carried out in a Laboratory abroad. In this study the concentrations of the following stable Isotopes were monitored.

- Deuterium - ^{2}H or D
- Oxygen18 ^{18}O
- Tritium - ^{3}H
- Carbon 14 ^{14}C
- Sulphur 34 ^{34}S

The results obtained from laboratory tests have been analyzed and the results are presented graphically.

The Figure 4.14 which is in the standard format of presenting isotope results gives a general picture of the isotopic distribution in the reservoir area. All the measured isotope signatures are almost lying on the Global Meteoric Water Line (GMWL) and have a wide spread along it.

The Figure 4.15 shows the of ^{18}O variation over time of leakage water (marked as main leak), river water and ground water from the selected locations

Similarly Figure 4.16 shows the ^{2}H variation over time of the water from the same sources as for the ^{18}O measurements.

Due to the complex nature of the leakage phenomenon, the test results do not indicate any straightforward information on the leakage flow paths.

However the following observations could be made. The isotope signatures of the leakage water and most of the ground water wells fall in between that of the two rivers, suggesting that leakage water could be considered as a mixer of waters from the two rivers. Also according to the graphs the leakage water and ground water represent a very similar behaviour with respect to both isotopes. Further it is notable that the isotopic signatures shown by the monitoring wells near the dam and far away from the dam are almost similar indicating an existence of a wide spread underground aquifer. This is further supported by the fact that all these monitoring wells in the right bank show a flat water table which is fluctuating with the reservoir water level. It is a possibility that the ground water in the aquifer has been replaced by the reservoir water which is a mixer of waters from two rivers. The reservoir water which infiltrate to the right bank aquifer through ingress zones initially got mixed with ground water locally and later has replaced ground water as the leakage outlet continue to discharge from right bank.. Considering the time elapsed between the initial leakage initiation in 1991 and the sampling period 2001 being about 10 years this possibility cannot be ruled out. Further, geologically this area had been subjected to karstification and the under ground cavernous nature prevailing has been confirmed during drilling and grouting operations conducted under remedial measures.

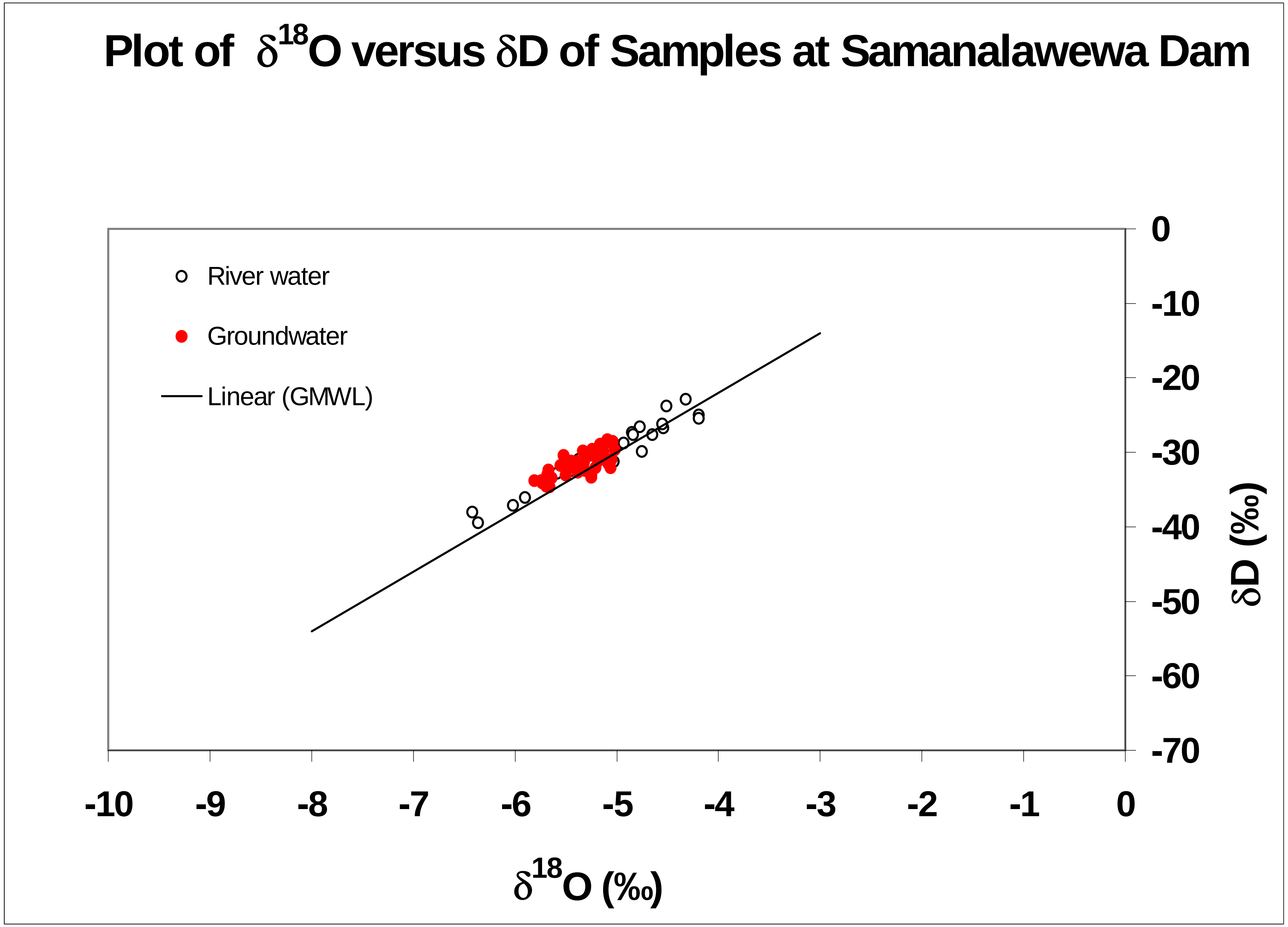


Figure 4.14 Standard representation of Isotope results

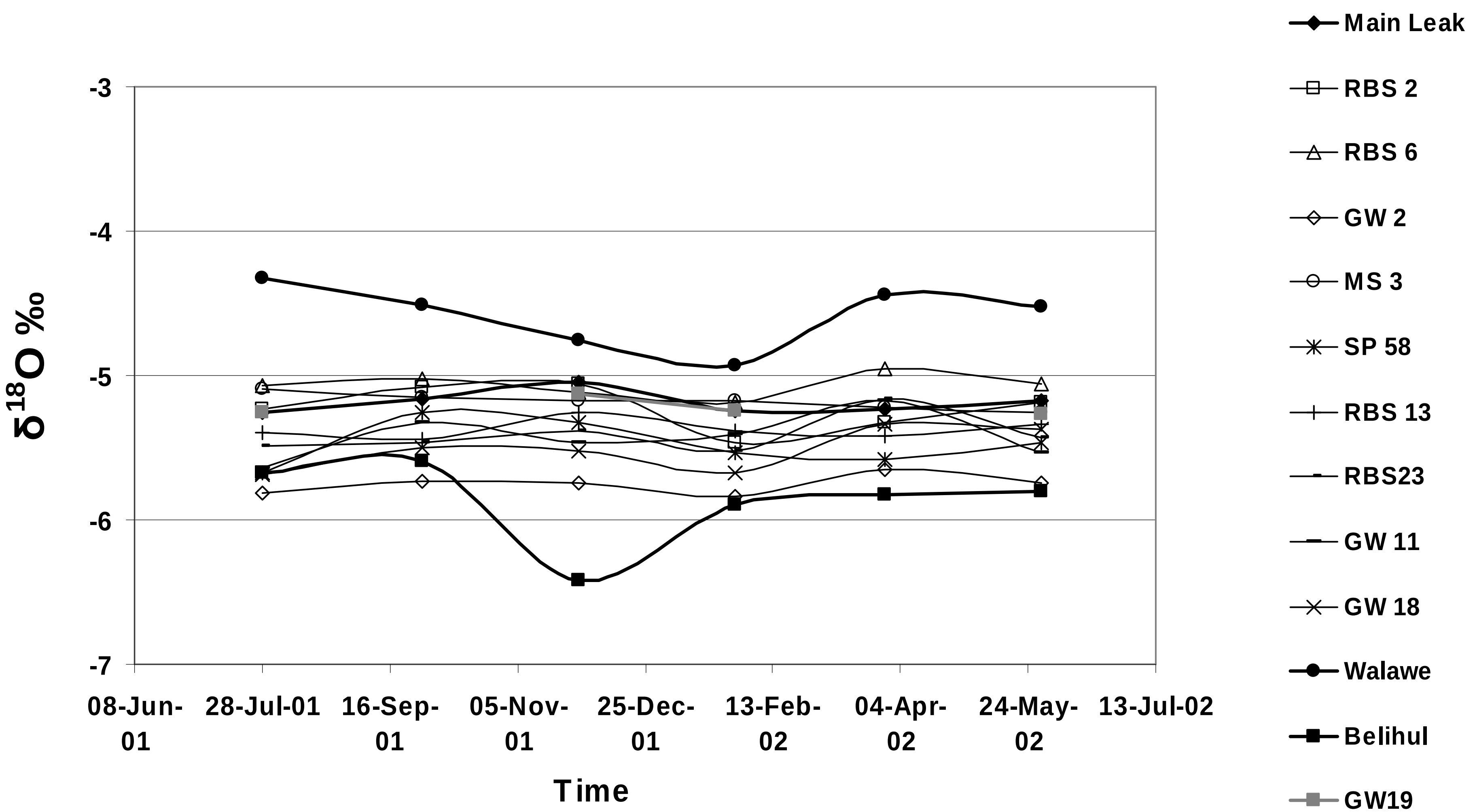


Figure 4.15 ^{18}O variation over time

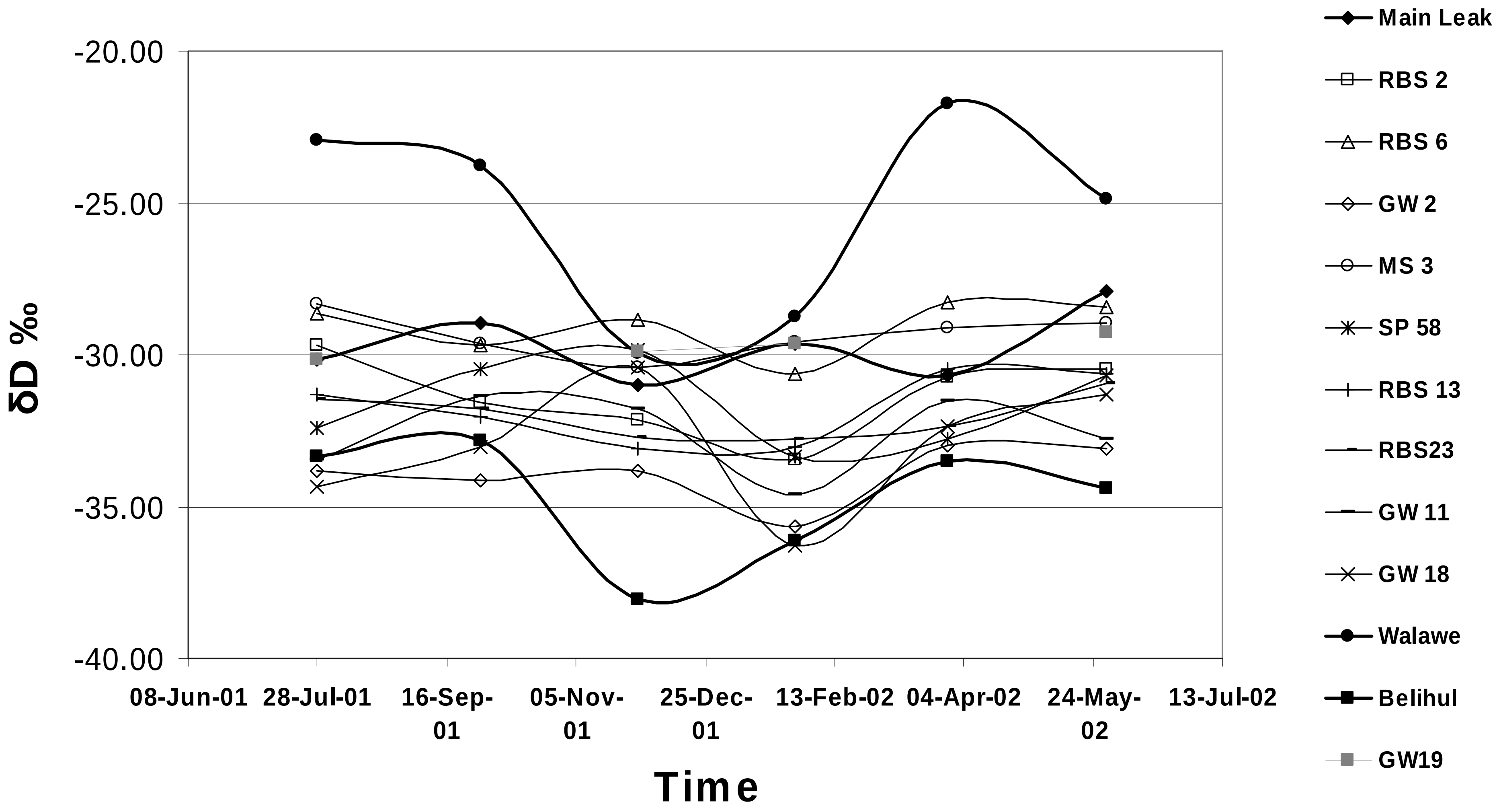


Figure 4.16 ^{2}H variation over time

During the planning of remedial measures, based on the geological findings it was established that the major leakage paths originating from the reservoir runs across the area where the stand pipe piezometers RBS 4, RBS 6 and the RBS10 are located. This was based on the fact that several major geological faults were cutting across the right bank in the same area and also based on the water chemistry studies. However according to isotopic signatures no specialty in the RBS 2 and RBS 6 over other ground water wells could be seen.

Unlike most geochemical tracers, ^{2}H and ^{18}O are inert and conservative in mixing relationships. Therefore stable isotopes can serve to quantify groundwater mixing at the local to catchment scale where mixing between ground waters of different recharge origins, from different aquifers and flow systems can take place. Mixing between two distinct water sources A and B could be represented by simple linear algebra as below.

$$\delta_{mixture} = X\ \delta_A + (1-X)\ \delta_B$$

Where $\delta_{mixture}$ is the $\delta^{2}H$ or $\delta^{18}O$ of the mixed water. X is the fraction of water source A in the mixture of A and B.

In this study the leakage water was considered as a mixture of original groundwater in the right bank and the reservoir water entering in to the right bank and attempt was made to derive the mixing proportions using the above equation. The isotopic concentrations of monitoring wells which are considered to be intact from leakage phenomenon were used to represent the original ground water in the right bank. Several computational trials were carried out using different wells representing original ground water conditions. However none of them resulted in a realistic value for the mixing proportion.

After analyzing the observed test results following conclusions can be made.

- The isotope signatures of leakage water and the ground water fall in between that of the two rivers feeding the reservoir. This indicates that over the years of leakage phenomenon ground water in the right bank has been replaced by the reservoir water.
- All the ground water wells monitored both surface and in grouting adit and left bank, leakage out let show a similar variation of isotopic signature with time. This confirms the existence of an underground aquifer extending to a larger extent along the right bank. This also indicates that river water movement takes place through out the right bank and any specific areas or paths cannot be clearly identified by this method. Also

the previously established leakage paths through the RBS4, RBS6, and RBS10 by other methods are no longer valid. Further the ground water holes like GW18 located far away (about 2.5 km) from the dam too show a similar variation with those of near the dam.

- No information on ground water and river water mixing could be derived suggesting that the ground water in the reservoir precincts has been already replaced with river water.
- Using the above results no conclusion could be made on the possible leakage paths and ingress zones which are necessary in planning the remedial measures. However existence of a common aquifer in the right bank is clearly understood. As the second phase of this study it is intended to carry out artificial isotope injection in the reservoir bed and in selected bore holes to find out the ground water movement directions. Using this technique it is also possible to estimate volume of the internal cavernous spaces by monitoring the ^{3}H variation in the leakage water and ground water over time. Therefore it is suggested to implement monitoring of the ^{3}H variation as the next step in order to get a clear picture of the right bank interior.

Chapter 5

Modeling and evaluation of the ground water level behaviour

5.1 General

In this chapter an attempt is made to evaluate the so far observed ground water level behaviour of the right bank. In this regard a two tank system is also engaged in modelling the right bank ground water level behaviour. This chapter gives an account of the evaluation carried out on the ground water level monitoring data.

5.2 Overall ground water level behaviour

According to the so far observed ground water level behaviour, except a few observation wells and piezometers who exhibit perched water table conditions, the majority of the observation wells and piezometers (more than three quarter) distributed over a vast area of the reservoir right bank and representing a common ground water regime indicate, that they all are emanating from a common source, i.e. an aquifer lying in side the right bank. Also the swift reaction of this common ground water regime to the reservoir water level changes, suggests that, this aquifer is in direct contact with the reservoir.

Further, it is noted that, except during the two transition events took place in 1992 and 1998 as a result of the burst and the earth blanket construction respectively, the common ground water regime existing in the right bank responds to the varying reservoir water level in a unique manner.

In this regard firstly the ground water level variation with respect to the reservoir water level during the period from 1993 to 1997 is considered. This period, between the right bank burst incident and the second remedial exercise, earth blanket construction could be considered as a period representing the normal behaviour of the tight bank aquifer due to several reasons. Firstly during this period reservoir water level was varying within the range of maximum and minimum water levels. And then no remedial measures or any other activity hampering the free flow conditions in the right bank, were carried out. The duration of this period being five years, is adequately sufficient to represent the stabilized flow conditions in the aquifer. Thus the ground water level response observed during this period represent the typical hydrogeological characteristics of the right bank with respect to the leakage mechanism.

To study the relationship between the right bank ground water level and the reservoir water level in detail, they have been plotted as shown in the following figures.

- Figure 5.1 - Ground water level against reservoir water level of GW and MS series observation wells (from 1993 to 1997)
- Figure 5.2 - Ground water level against reservoir water level of RBS series standpipe piezometers (from 1993 to 1997)
- Figure 5.3 - Ground water level against reservoir water level of SP series standpipe piezometers (from 1993 to 1997)

In preparing the above figures only the observation wells and standpipe piezometers which are behaving in a similar manner have been considered.

There are few observation wells and standpipe piezometers which behave differently and independent of the reservoir water level. They are few in number and indicate perched water table conditions and behave as isolated individual pockets and not connected to the right bank aquifer. Their behaviour is discussed elsewhere.

As this figures depicts, the ground water level and the reservoir water level correlation is linear (with an average slope of 0.82), and can be mathematically represented as

$$GWL = m.RWL + c \quad (1)$$

Where

RWL: Reservoir water level

GWL: Ground water level

and 'm' and 'c' are constants

This is common for those observation wells and standpipe piezometers lying close to the dam as well as those installed at the far end of the dam.

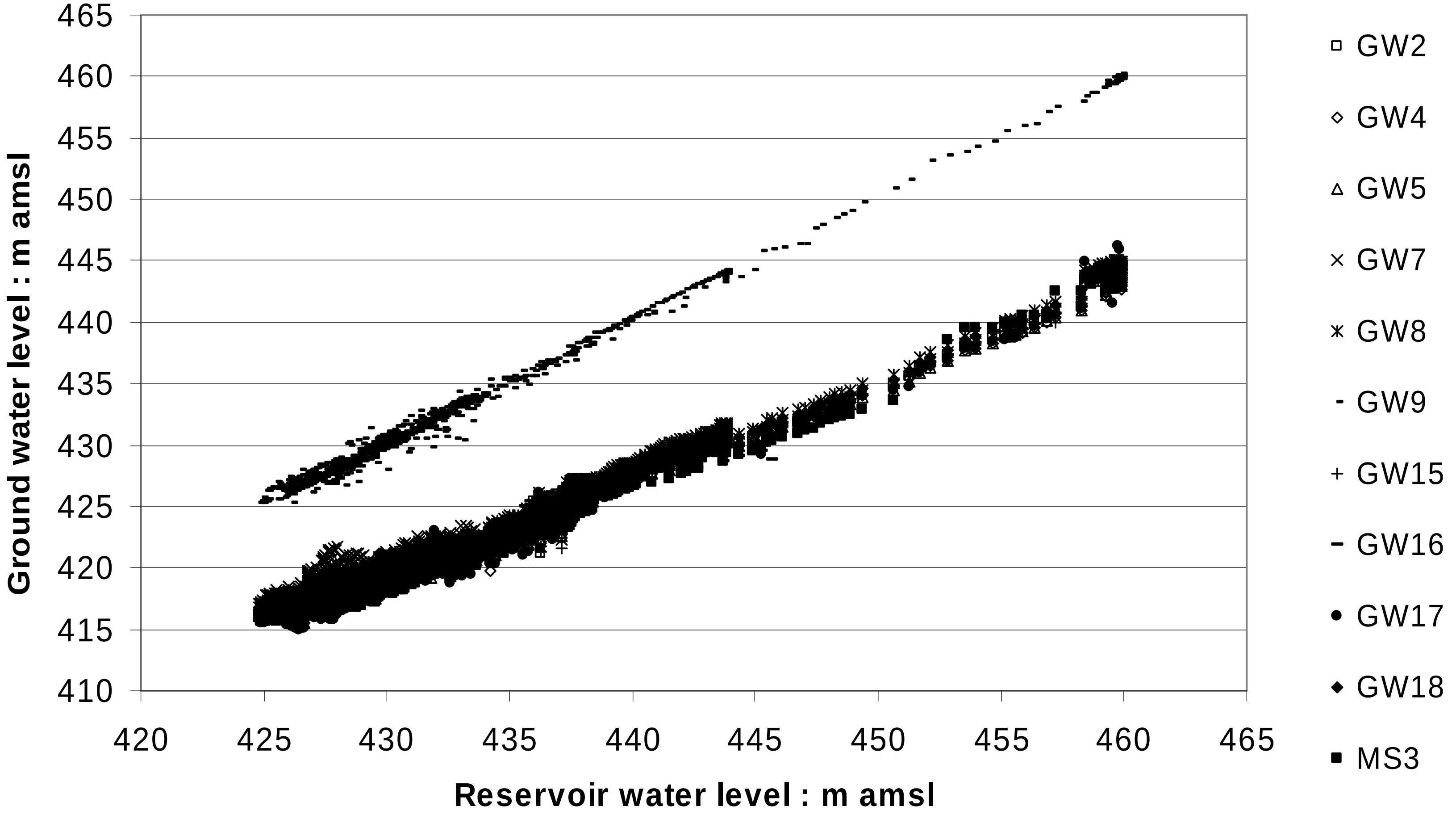


Figure 5.1 Ground water level against reservoir water level of GW and MS series observation wells during 1993 - 1997

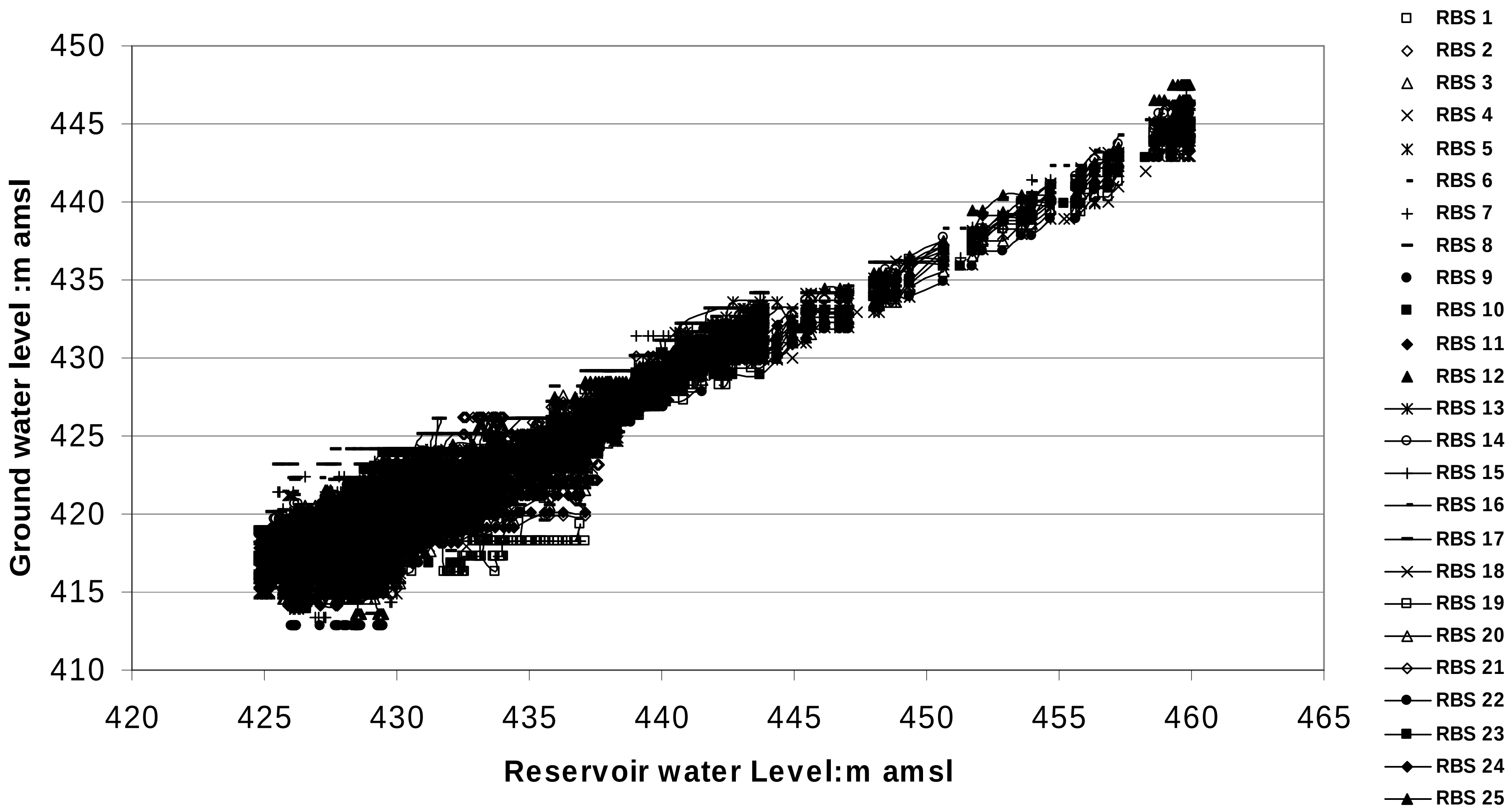


Figure 5.2 Ground water level against reservoir water level of RBS series piezometers during 1993 - 1997

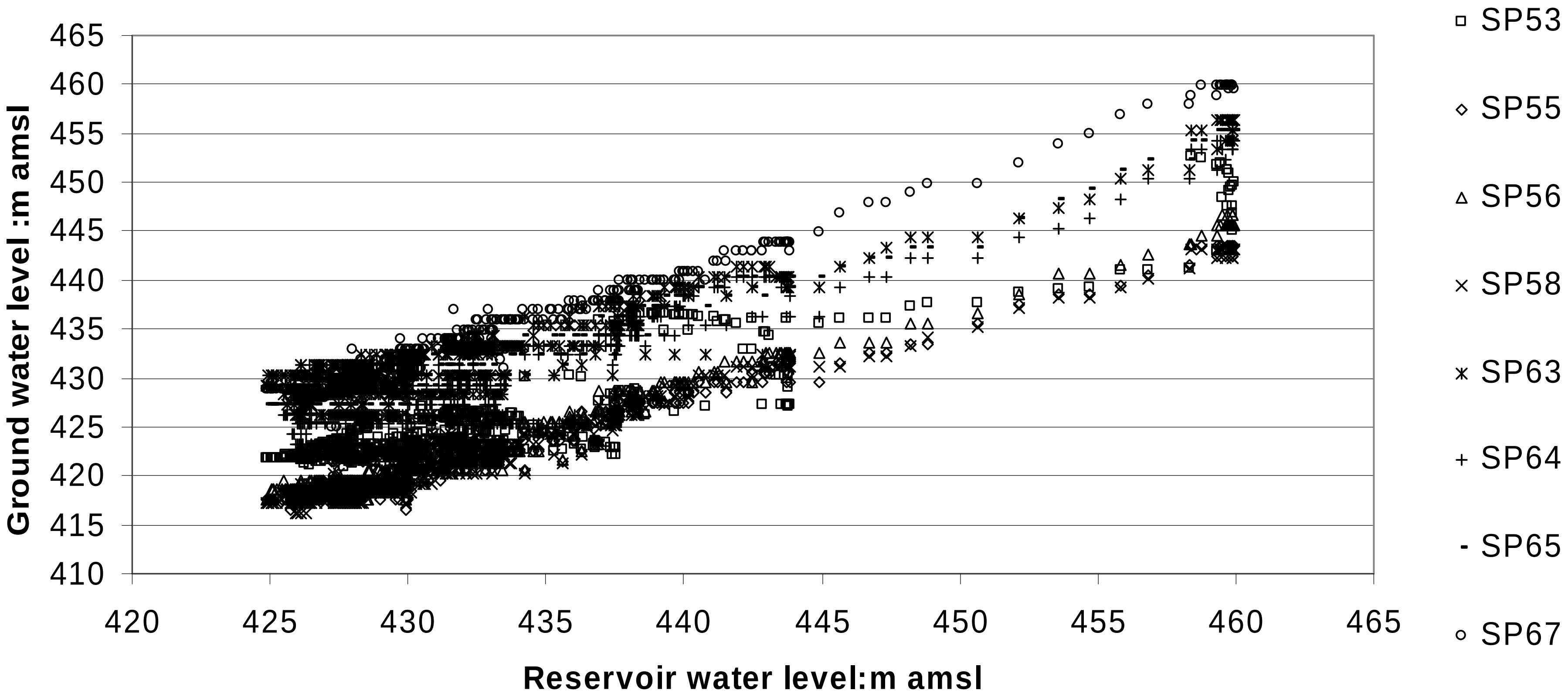


Figure 5.3 Ground water level against reservoir water level of SP series piezometers during 1993 – 1997

The derived slope values ('m') of all the observation wells and piezometers which are behaving in a similar pattern are presented in Figure 5.4, to emphasize the similarity in behaviour shown by them.

In the Table 5.1 calculated slope values for the GW and MS series observation wells are presented. Similarly those of the RBS and SP series standpipe piezometers are given in Table 5.2. As the two tables show both the observation wells and standpipe piezometers show an average slope value of 0.82 during the considered period. This is a very important and special characteristic of the right bank aquifer. The Table 5.3 shows the summary of the behaviour patterns of all the observation wells and piezometers based on the so far observed ground water response.

Similarly, when the behaviour of the right bank during 1999 to 2005, i.e. after the earth blanket construction is considered, an equal correlation between the ground water level and the reservoir water level can be observed with an average slope of 0.62.

The following figures show the right bank ground water level variation against reservoir water level during the period 1999 to 2005.

- Figure 5.5 - Ground water level against reservoir water level of GW and MS series observation wells (from 1999 to 2005)
- Figure 5.6 - Ground water level against reservoir water level of RBS series standpipe piezometers (from 1999 to 2005)
- Figure 5.7 - Ground water level against reservoir water level of SP series standpipe piezometers (from 1999 to 2005)

This is the period, just after the completion of the earth blanket construction works and during this period the reservoir was operated without any remedial measures being implemented. As mentioned earlier, during the earth blanket construction the ground water level dropped suddenly with a slight reduction in the leakage flow rate as one leakage ingress opening (called block 'X') in the river bed got closed.

As observed in the above graphs even after a 10m drop in the ground water level as a result of earth blanket construction, the right bank ground water behaviour shows a linear variation against reservoir water level changes.

Table 5.1 Slope values of the GWL against RWL plot of GW and MS series observation wells during 1993 - 1997

Observation well No.	Slope	Correlation coefficient (R^2)	Remarks
GW 1	0.823	0.837	1 year data
GW 2	0.795	0.984	
GW 3	0.872	0.926	
GW 4	0.798	0.987	
GW 5	0.797	0.987	
GW 6	0.786	0.912	
GW 6A	0.810	0.970	
GW 7	0.778	0.982	
GW 8	0.817	0.987	
GW 9	0.996	0.996	
GW 10	-	-	Out of service
GW 11	-	-	No relationship
GW 12	0.754	0.907	
GW 13	-	-	No relationship
GW 14	-	-	No relationship
GW 15	0.804	0.987	
GW 15A	-	-	No relationship
GW 16	0.823	0.992	3 years data
GW 17	0.811	0.984	
GW 18	0.810	0.987	
MS 1	-	-	No relationship
MS 2	-	-	No relationship
MS 3	0.797	0.987	
Average	0.816		

Table 5.2 Slope values of the GWL against RWL plot of RBS and SP series piezometers during 1993 - 1997

Standpipe piezometer	Slope	Correlation coefficient (R2)	Remarks
RBS 1	0.808	0.928	
RBS 2	0.834	0.917	
RBS 3	0.899	0.854	
RBS 4	0.839	0.939	
RBS 5	0.840	0.933	
RBS 6	0.793	0.933	
RBS 7	0.863	0.947	
RBS 8	0.855	0.935	
RBS 9	0.852	0.935	
RBS 10	0.771	0.936	
RBS 11	0.851	0.885	
RBS 12	0.787	0.959	
RBS 13	0.820	0.966	
RBS 14	0.826	0.930	
RBS 15	0.856	0.957	
RBS 16	0.850	0.855	
RBS 17	0.804	0.940	
RBS 18	0.875	0.845	
RBS 19	0.781	0.886	
RBS 20	0.822	0.950	
RBS 21	0.821	0.939	
RBS 22	0.799	0.956	
RBS 23	0.841	0.961	
RBS 24	0.848	0.919	
RBS 25	0.853	0.952	
RBS 26	-	-	No relationship
RBS 27	-	-	No relationship
RBS 28	-	-	No relationship
RBS 29	-	-	No relationship
RBS 30	-	-	No relationship
RBS 31	-	-	No relationship
SP53	0.734	0.830	
SP55	0.769	0.974	
SP56	0.823	0.974	
SP58	0.772	0.955	
SP63	0.764	0.880	
SP64	0.777	0.790	
SP65	0.819	0.961	
SP67	0.970	0.838	
SP69	0.809	0.966	
Average	0.824		

Table 5.3 summary behaviour (based on 1993-1997 period)

Category	Observation well/standpipe piezometer No	Observed behaviour
Observation wells	GW1,GW2,GW3,GW4,GW5,GW6,GW6A, GW7,GW8,GW9,GW12,GW15,GW16,GW 17,GW18and MS3	Exhibit a linear relationship with an average slope of 0.816 in the ground water level versus reservoir water level plot
	GW11,GW13,GW14,GW15A,MS1,MS2	No relationship between ground water level and reservoir water level is observed
Stand pipe piezometers	RBS 1 to RBS 25 and SP53 to SP69	Exhibit a linear relationship with an average slope of 0.824 in the ground water level versus reservoir water level plot
	RBS26 toRBS31	No relationship between ground water level and reservoir water level is observed

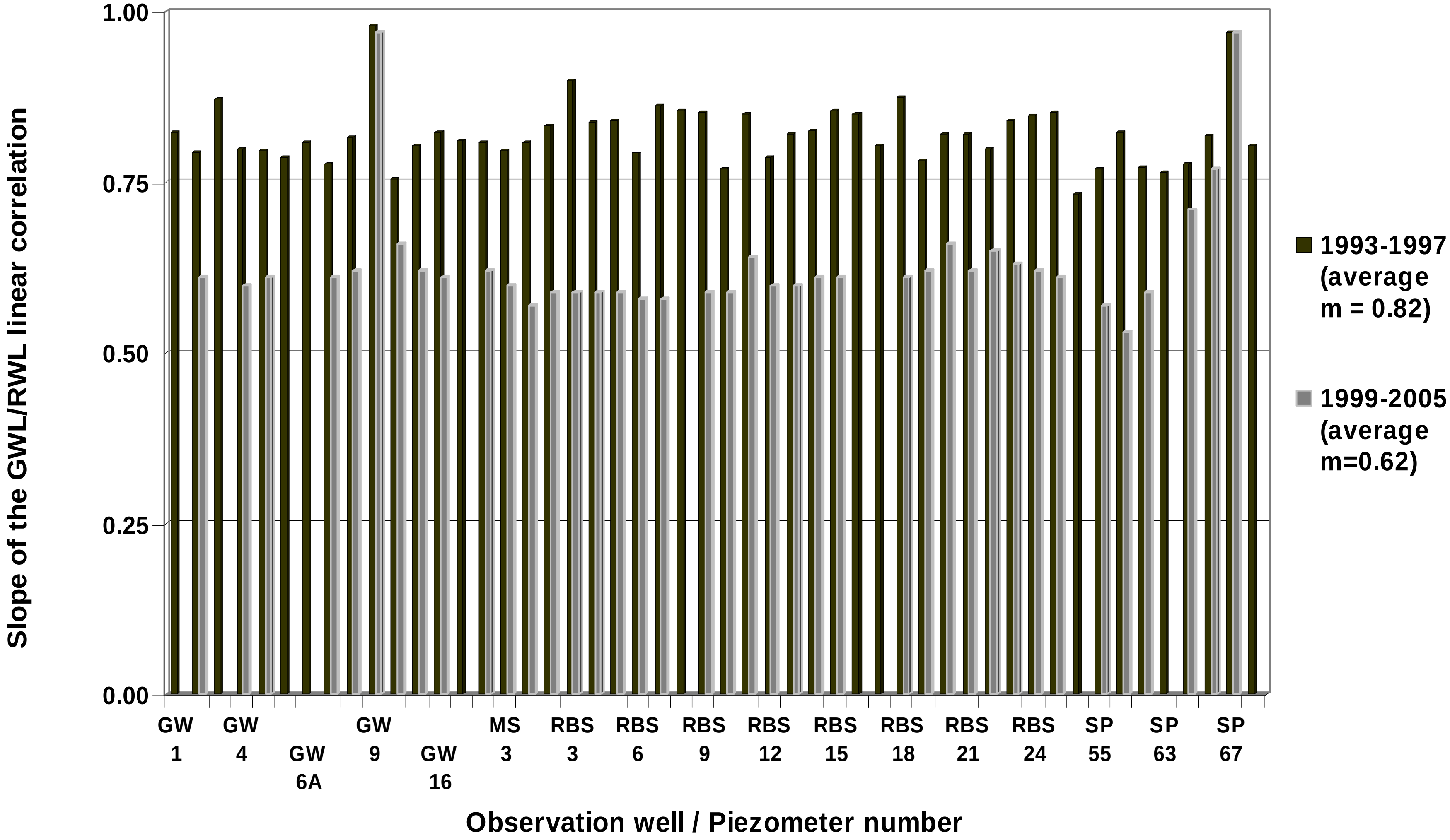


Figure 5.4 Slope values of the ground water level- reservoir water linear correlation

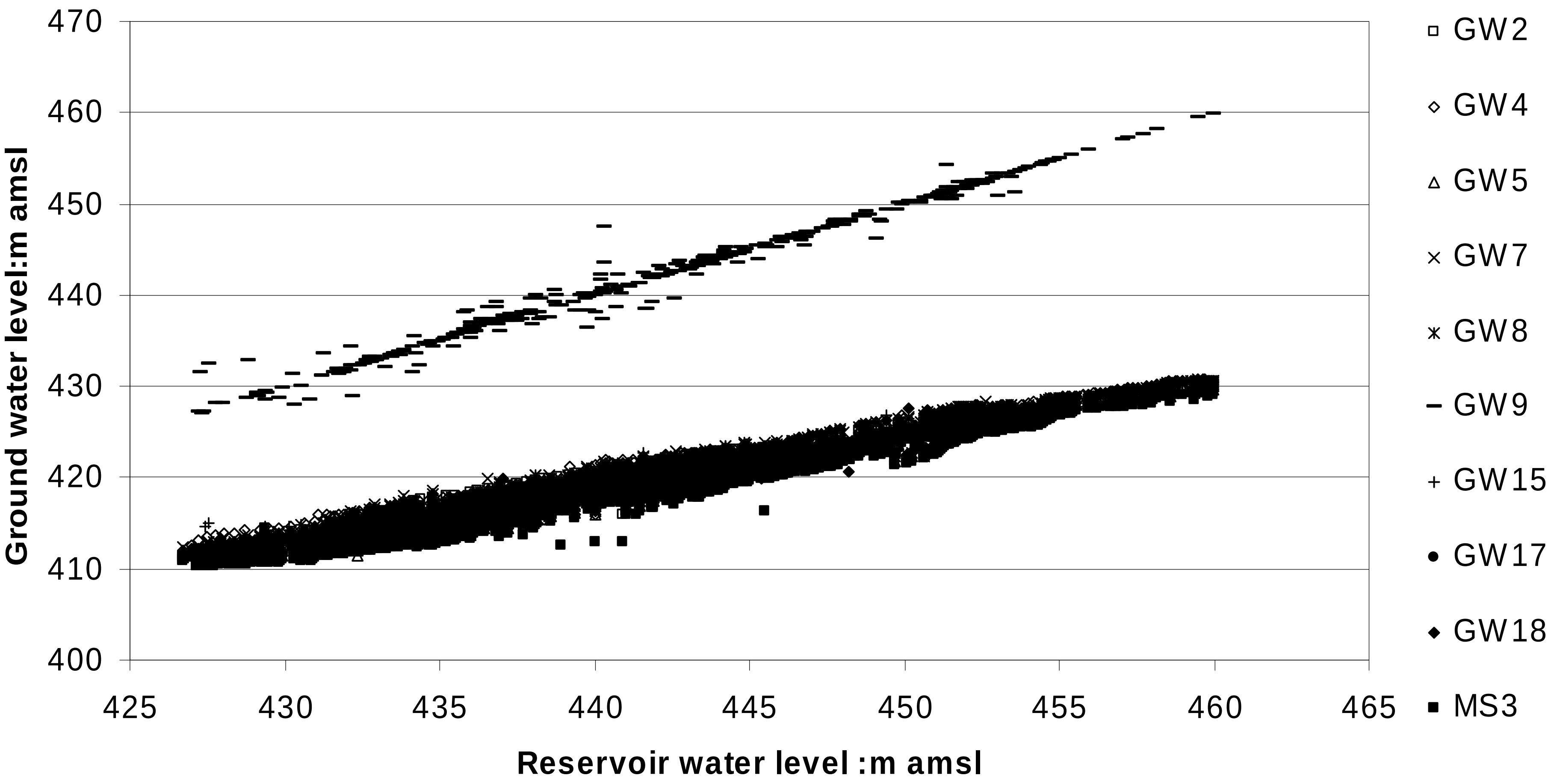


Figure 5.5 Ground water level against reservoir water level of GW and MS series observation wells during 1999 - 2005

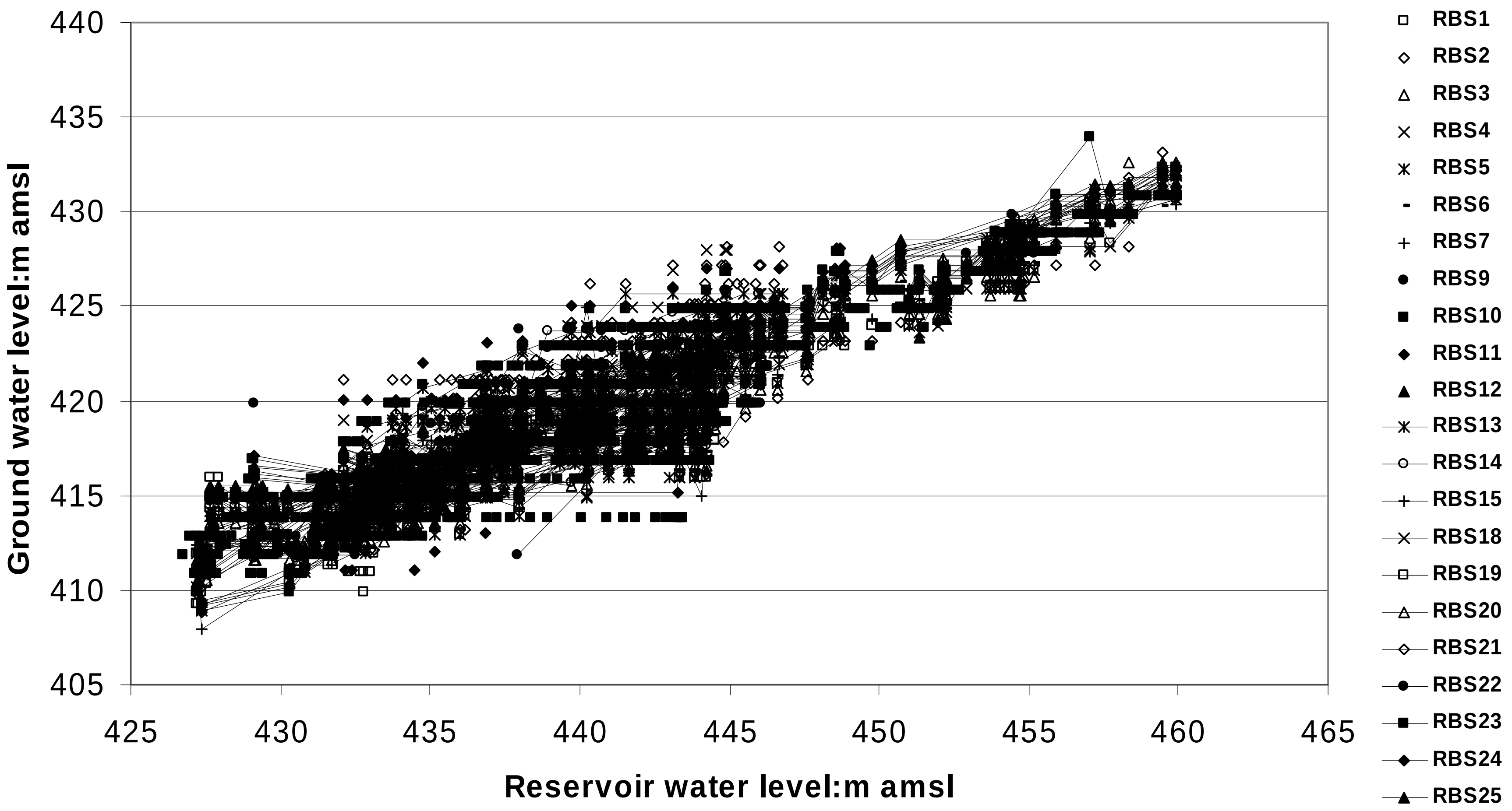


Figure 5.6 Ground water level against reservoir water level of RBS series piezometers during 1999 - 2005

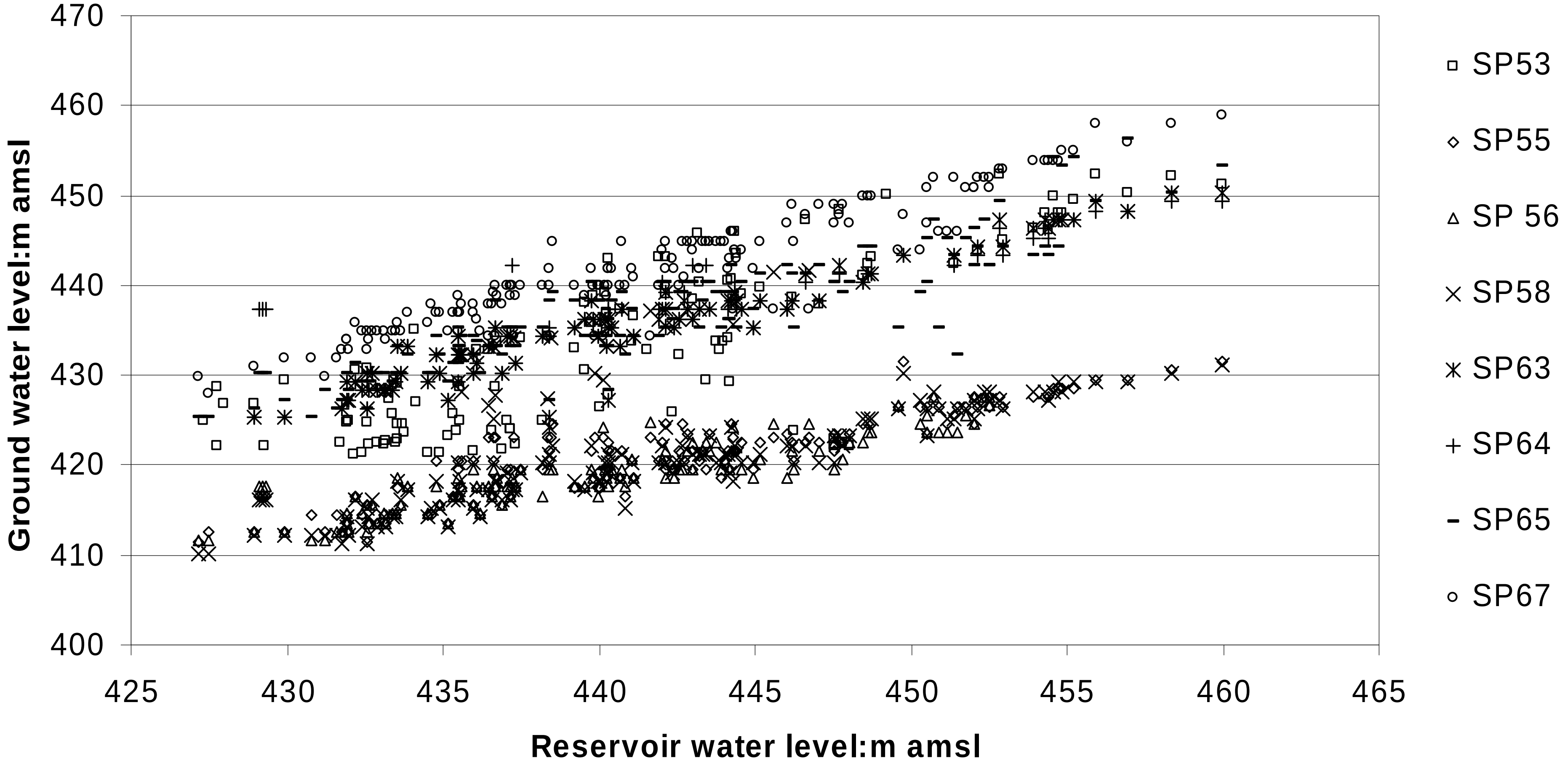


Figure 5.7 Ground water level against reservoir water level of SP series piezometers during 1999 – 2005

However the slope of the line has dropped giving average values of 0.62 for GW and SP series observation wells and 0.61 for the RBS and SP type standpipe piezometers. The slope values derived for each bore hole and standpipe piezometer are given in the Table 5.4 ,GW and SP series observation wells and Table 5.5 RBS and SP type standpipe piezometers. They are also presented in graphical format in the Figure 5.4 in combination with the previous results.

Thus the above observed correlation existing between the right bank ground water level and the reservoir water level is a characteristic feature of the right bank aquifer, with respect to the leakage mechanism and need to be studied in detail. In this regard, the reservoir and the right bank aquifer which is behaving as an underground reservoir resemble a two interconnected reservoir system. Hence a two interconnected reservoir model could be used as presented below to study the ground water level and reservoir water level correlation in detail.

5.3 Two Tank System (Tank Model)

As an attempt in understanding the above characteristics observed in the ground water level data analysis let's consider a simple two interconnected tank system. The Figure 5.8 shows the schematic view of the considered tank model.

The two tanks are connected with a pipe located towards the bottom and the second tank is open to atmosphere with an outlet as shown.

The hydraulic relationship of the flow between the two tanks and to the outside can be mathematically represented according to Bernoulli's theorem as follows.

applying Bernoulli's theorem for the first tank

when $H_{2t} > H_i > H_0$

$$Q_{1t} = K_1 (H_{1t} - H_{2t})^{1/2} \tag{2}$$

$$K_1 = a_1 n_1 (2g)^{1/2} \tag{2a}$$

Table 5.4 Slope values of the ground water level against reservoir water level plot of GW and MS series observation wells during 1999 - 2005

Observation well No.	Slope	Correlation coefficient (R^2)	Remarks
GW 1	-	-	Out of service
GW 2	0.61	0.965	-
GW 3	-	-	Not linear
GW 4	0.60	0.959	-
GW 5	0.61	0.966	-
GW 6	0.43	0.693	Not linear
GW 6A	-	-	Not linear
GW 7	0.61	0.960	-
GW 8	0.62	0.964	-
GW 9	0.98	0.984	-
GW 10	-	-	-
GW 11	0.51	0.326	GWL high
GW 12	0.66	0.939	GWL high
GW 13	-	-	-
GW 14	-	-	-
GW 15	0.62	0.963	-
GW 15A	-	-	Not linear
GW 16	0.61	0.418	
GW 17	0.48	0.965	
GW 18	0.62	965	-
MS 1	-	-	-
MS 2	-	-	Constant with time
MS 3	0.60	0.957	-
Average	0.62		

Table 5.5 Slope values of the ground water level against reservoir water level plot of RBS and SP series piezometers during 1999 - 2005

Standpipe piezometer	Slope	Correlation coefficient (R^2)	Remarks
RBS 1	0.57	0.852	
RBS 2	0.59	0.730	
RBS 3	0.59	0.885	
RBS 4	0.59	0.813	
RBS 5	0.59	0.889	
RBS 6	0.58	0.906	
RBS 7	0.58	0.887	
RBS 8	-	-	No relationship
RBS 9	0.59	0.805	
RBS 10	0.59	0.839	
RBS 11	0.64	0.828	
RBS 12	0.60	0.891	
RBS 13	0.60	0.839	
RBS 14	0.61	0.882	
RBS 15	0.61	0.894	
RBS 16	-	-	No relationship
RBS 17	-	-	No relationship
RBS 18	0.61	0.904	
RBS 19	0.62	0.907	
RBS 20	0.66	0.913	
RBS 21	0.62	0.909	
RBS 22	0.65	0.881	
RBS 23	0.63	0.910	
RBS 24	0.62	0.905	
RBS 25	0.61	0.925	
RBS 26	-	-	No relationship
RBS 27	-	-	No relationship
RBS 28	0.48	0.858	
RBS 29	-	-	No relationship
RBS 30	-	-	No relationship
RBS 31	-	-	No relationship
SP53	0.96	0.621	
SP55	0.57	0.810	
SP56	0.53	0.796	
SP58	0.59	0.528	
SP63	0.82	0.897	
SP64	0.71	0.816	
SP65	0.77	0.799	
SP67	0.97	0.881	
SP69	0.90	0.662	
Average	0.61		

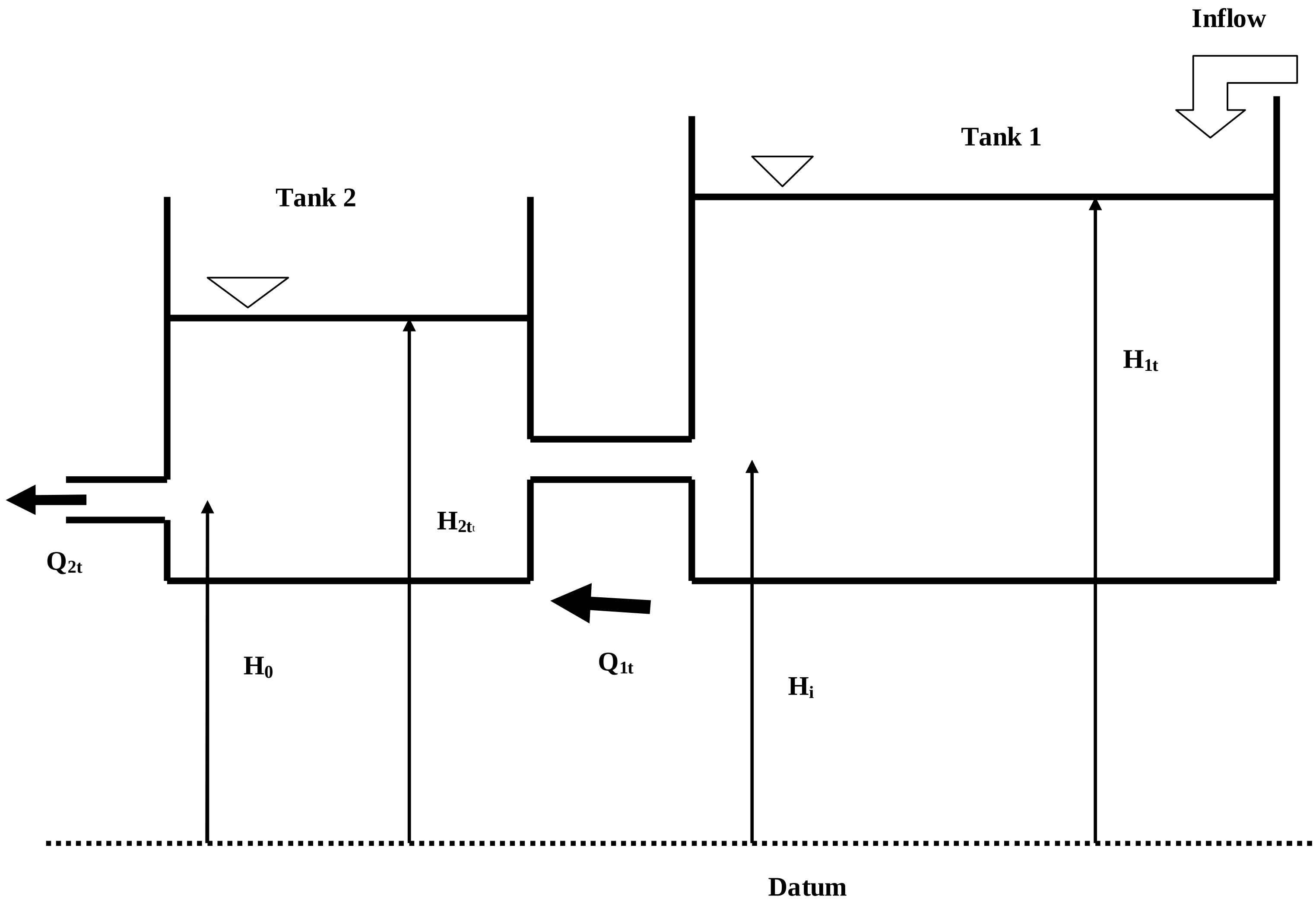


Figure 5.8 Lay out of the two tank model

Similarly for the second tank

$$Q_{2t}= K_2 (H_{2t} – H_0)^{1/2} \qquad (3)$$

$$K_2 =a_2 n_2(2g)^{1/2} \qquad (3a)$$

where

Q_{1t}–flow rate from first tank to the second tank at time t

Q_{2t} – discharge from the second tank to the outside

H_{1t} – water level in the first tank at time t

H_{2t} – water level in the second tank at time t

H_0 - elevation of the outlet

H_i - elevation of the inlet

(all the above levels are given with respect to the datum line).

a_1 – tank 1 to tank 2 inlet cross sectional area

n_1 – loss coefficient, depends on the tank 1 to tank 2 inlet cross section and the head loss between the tanks

a_2 – tank 2 outlet cross sectional area

n_2 – loss coefficient, depends on the tank 2 outlet cross section and the head losses at the outlet

g – acceleration of gravity

When the two tank system is in equilibrium condition, the inflow from tank 1 to tank 2 is equal to the outflow of the tank 2.

Therefore Q_{1t} equals to Q_{2t}.

And hence the equations (2) and (3) become

$$K_2 (H_{2t} – H_0)^{1/2} = K_1 (H_{1t} – H_{2t})^{1/2}$$

rearranging the above equation

$$H_{2t} = K_3 / (1+ K_3) H_{1t} + H_0/ (1+ K_3) \qquad (4)$$

Where $K_3 = K_1^2 / K_2^2$

The above equation (4) shows a linear relationship between the water levels of two water tanks as the other parameters are constants.

5.4 Assessment of ingress areas

The hydraulic relationship obtained from the two tank model can be used to attempt a quantitative assessment of the leakage ingress areas.

By referring to earlier two tank model and taking the square of both sides of above equations (2) and (3),

(2) becomes

$Q^2_{1t} = K^2_{\ 1} (H_{1t} - H_{2t})$ …….. (5)

similarly from (3)

$Q^2_{2t} = K^2_{\ 2} (H_{2t} - H_0)$……….. (6)

In the above equations (5) and (6), the terms square of discharge and the head difference are taken as variables and then their relationship show a linear variation as the 'K' values are constant.

Thus by plotting square of discharge (Q^2) against the head difference for two reservoirs the constants K_1 and K_2 could be determined.

Therefore using the above equations in the reservoir right-bank system, equivalent cross sectional areas of the leakage inlets and outlet can be worked out. In this regard, H_1 and H_2 become reservoir water level and ground water level respectively. The ground elevation of the leakage outlet is 392 m amsl and therefore H_0=392 m.

Hence as shown in Figures 5.9 and 5.10 two plots can be prepared using the available reservoir water level, ground water level data and leakage flow rate data for the periods 1993 to 1997 and 1999 to 2005, separately.

Referring to the Figures 5.9and 5.10

$K^2_{\ 1}$= 0.354 during 1993 -1997 (from Figure 5.9) and = 0.175 during 1999-2005 (from Figure 5.10)

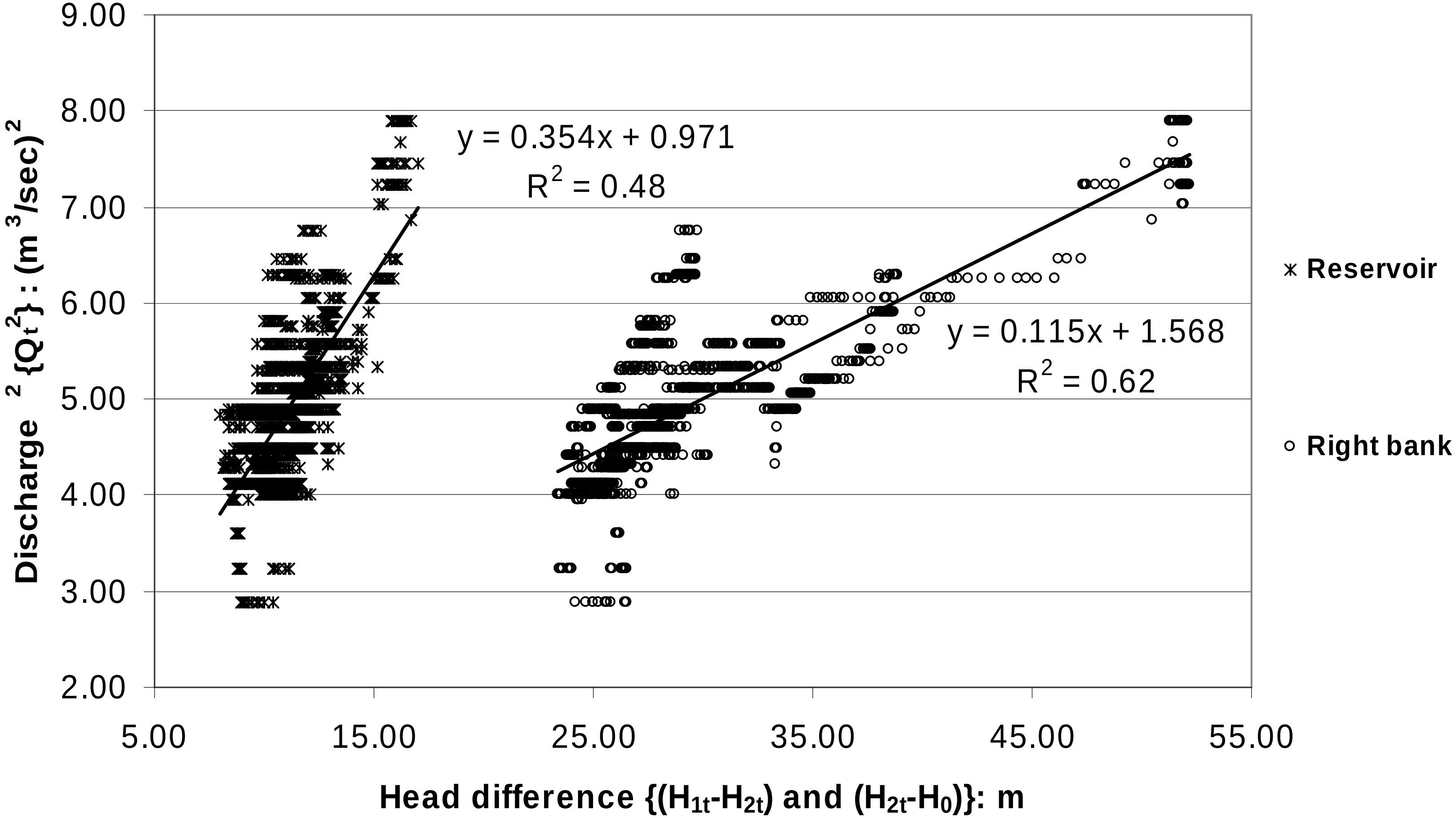


Figure 5.9 Square of discharge against the head difference for the period 1993 - 1997

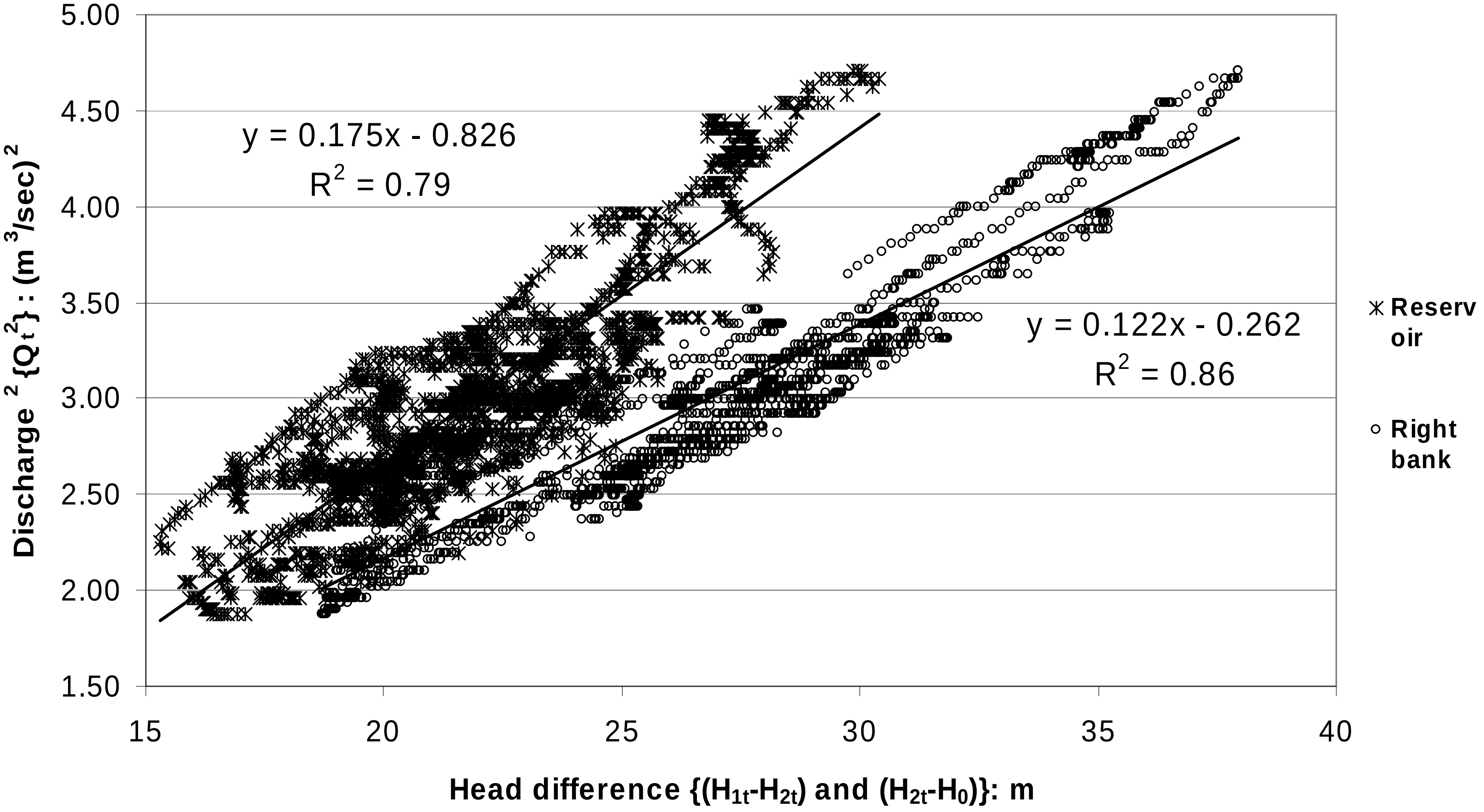


Figure 5.10 Square of discharge against the head difference for the period 1999 - 2005

Similarly

$K^2{}_2$ = 0.115 during 1993 -1997 (from Figure 5.9) and = 0.122 during 1999-2005 (from Figure 5.10)

Using the above results in equations (1a) and (2a), equivalent inlet and outlet cross sectional areas a_1 and a_2 can be worked out.

$K_1 = a_1 n_1 (2g)^{1/2}$ ………….(1a)

and

$K_2 = a_2 n_2 (2g)^{1/2}$ ………….. (2a)

In the above equations (1a) and (2a), the applicable coefficient of discharge values, n_1 and n_2 are unknown before hand.

However it has been shown that for this type of two tank systems the loss coefficient values in the range of 0.98 to 0.60 are applicable. Therefore the values of a_1 and a_2 are calculated for the above range of n_1 and n_2 values as given in Table 5.6 below. The Figure 5.11 shows the graphical presentation of the calculated a_1 and a_2 (equivalent cross sectional areas) values.

According to the above table, the equivalent cross sectional areas of the inlet and outlet are found to be of the same order.

Further the derived equivalent cross sectional area of the out let tallies with the actual cross sectional area of the main leakage outlet, which is found to be in the range of 0.10 to 0.20 m^2.

Therefore based on the above results it can be deduced that the equivalent cross sectional area of the leakage inlets in the reservoir are also in the order of 0.12 to 0.15 m^2.

Table 5.6 Equivalent cross sectional areas of the leakage inlets and outlet

Equivalent cross sectional areas					
Leakage inlets – a_1 (m^2)			**Leakage outlet – a_2 (m^2)**		
n_1	**1993-1997**	**1999-2005**	**n_2**	**1993-1997**	**1999-2005**
0.98	0.14	0.10	0.98	0.08	0.08
0.90	0.15	0.10	0.90	0.08	0.09
0.80	0.17	0.12	0.80	0.10	0.10
0.70	0.19	0.13	0.70	0.11	0.11
0.60	0.22	0.16	0.60	0.13	0.13

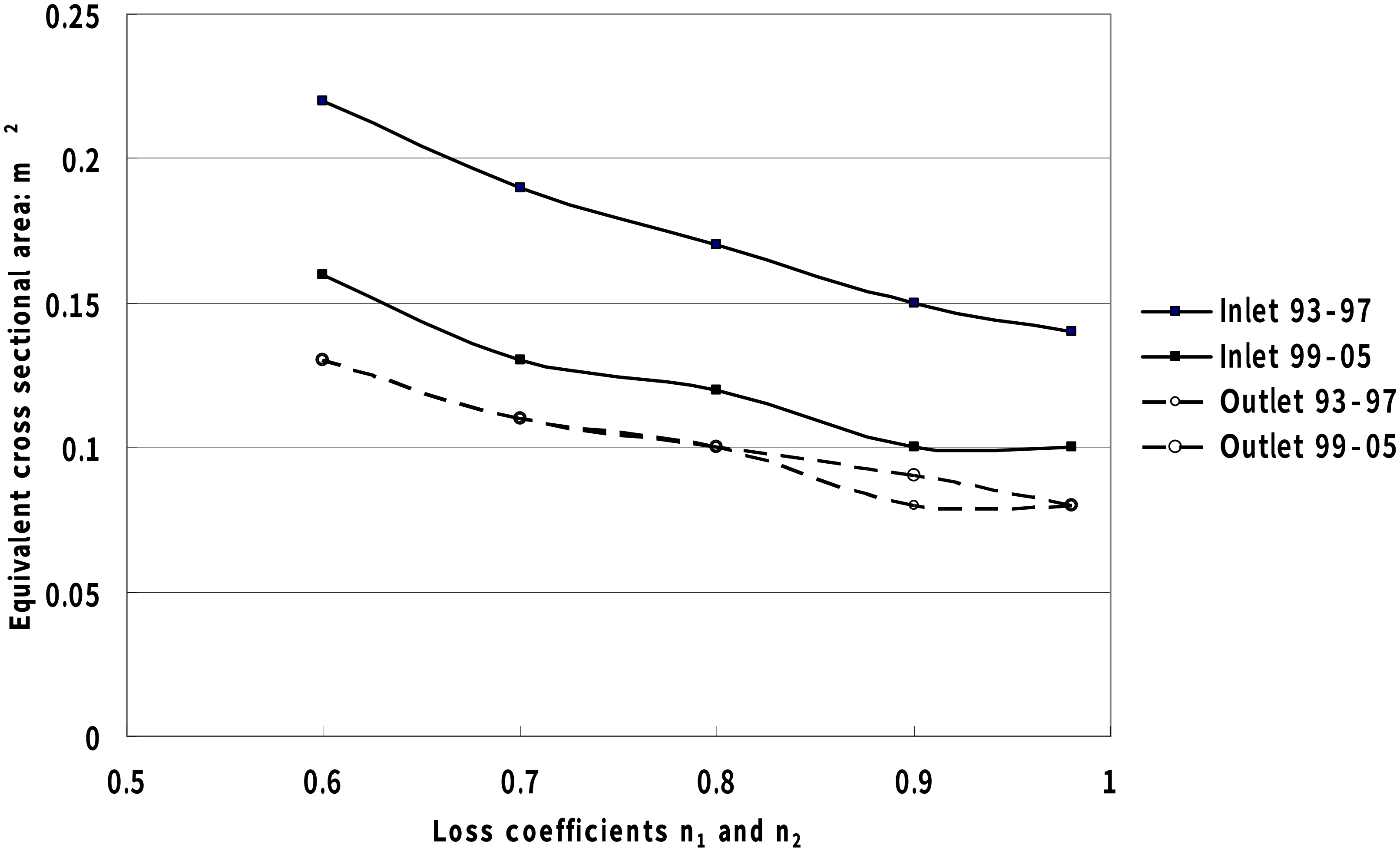


Figure 5.11 Graphical representation of equivalent cross sectional areas

Chapter 6

Investigation of the leakage mechanism

6.1 General

In this chapter an attempt is made to establish the leakage mechanism based on the so far made observations on geological aspects and hydrogeological aspects. Firstly the consideration is given to the hydro geological behaviour evaluated so far and then a correlation is established with the hydrogeological findings and the geological observations.

6.2 The leakage mechanism based on hydrogeological aspects

The results obtained in the previous chapter using the two tank system can be used in explaining the right bank ground water level behaviour observed considering the following similarities observed in the tank model and the reservoir/right bank system.

In general the reservoir and the right bank can be considered as two interconnected tanks with the main leakage point representing the outlet of the second tank.

The equal ground water level response shown by the majority of the observation wells and piezometers including those installed at the far away from the dam indicates the existence of a widely spread aquifer resembling an underground reservoir.

Further the cross sectional area of the main leakage outlet do not change with time as observed during last 15 years and the leakage water flow was mainly restricted to the main leakage outlet. The main leakage outlet releases more than 95% of the total leakage and the other minor leakage outlets which are lying close to the main outlet could be considered to be incorporated in the main leakage outlet without much error. Therefore the sectional area and the roughness conditions at the outlet could be considered as constant.

Also as observed during the right bank ground water level monitoring, the right bank ground water level responds within 10 to 15 hours of a change in the reservoir water level. This has been exhibited by all the observation wells and piezometers in the right bank, which are behaving in a similar pattern. Except during such short transition time periods, the reservoir water level and the right bank water level are in a stabilized state indicating balanced inflow and outflow conditioned in the right bank.

Thus it shows that the right bank and the reservoir act as a two interconnected tank system and the linear relationship observed between the water levels of the two tanks is equivalent to the linear relationship observed between the ground water level and the reservoir water level.

Hence it further suggests that the reservoir and the right bank act as two interconnected tanks with specific inlets and outlets. Thus can be concluded that the inlet/inlets are lying below the minimum observed water levels i.e. the inlets are lying towards the bottom of the reservoir and not on upper slopes. This is a very important conclusion with regard to the reservoir leakage mechanism.

6.3 Change of situation after earth blanket construction

Further the above results can be used to understand the ground water level behaviour observed during 1999 to 2005 period, where the slope of the linear correlation of reservoir water level and ground water level reduced from 0.82 to 0.62.

This reduction in slope value from 0.82 before earth blanket construction to 0.62 after earth blanket construction can be explained in the following manner.

The reduction in slope value results in the reduction in k_3 value.

slope = $K_3 / (1+ K_3)$

and $K_3 = K_1^2 / K_2^2$

as K_3 = slope / (1- slope)

Thus when slope reduces from 0.82 to 0.62, the K_3 reduces from 4.56 to 1.63.

Reduction in K_3 is possible only by a reduction in K_1 value or by an increase in K_2 value. However as there was no change in the leakage outlet conditions, K_2 remains constant. The K_1 value is proportional to the inlet cross sectional area at the leakage ingress area. As observed, during earth blanket construction a leakage inlet in the block `X` area got sealed. Therefore it can be concluded that sealing of the block 'X' area resulted in reducing the leakage inlet cross sectional area causing a reduced K_1 value.

The above results can be further used in estimating approximately the extent of the leakage inlet cross sectional area got sealed during wet blanketing.

It is assumed that the conditions at the leakage outlet do not vary during this period (this has been observed at site also) and also the roughness conditions at the inlet remain constant.

before wet blanket construction $K_3 = K_1^2 / K_2^2 = 4.56$

and

after wet blanket construction $K_3 = K_1^2 / K_2^2 = 1.63$

Therefore the ratio of K_1 after wet blanket construction to K_1 before wet blanket construction becomes.

$K_{1\,after} / K_{1before} = 0.597$

As this is proportional to the inlet cross sectional area, it can be concluded that approximately about 40% of the total leakage ingress area (inlets) has been sealed by earth blanket construction and the remaining inlet area is only 60% of the original ingress area.

6.4 Correlation with the geological findings

As observed in the geological aspects of the project area, the various investigations conducted under different periods provide ample evidence on the nature of the right bank. Basically according to the permeability tests the many of the boreholes indicate heavy water losses and high Lugeon values. Further the drill rods drops and the cavities encountered during drilling provide strong evidence of the porous nature of the right bank. A number of surface caves, which are extending in to the right bank surface were found during the excavations for the dam right abutment. Thus it shows that the porous structure of the right bank caused by the karstification extends throughout from exterior to interior. This porous nature of the right bank has been facilitating the fast and swift movement of the ground water within right bank as observed with the reservoir impounding. As observed in the 15 year long ground water monitoring record, the ground water level through out the right bank has been responding to the reservoir water level changes in a swift manner resembling a two interconnected tanks. Also the linear correlation observed between the ground water level and the reservoir level suggests that such hydraulic connections have to be through unique inlets between the two tanks. Thus according to the geological nature of the right bank such inlets can be one or few undetected karstic cavity openings on the right bank surface and lying at low levels.

6.5 Possible locations of leakage inlets

As so far observed the two tank model adequately explain the behaviour of the right bank with respect to the leakage phenomenon. Further a closer look at the ground water level behaviour of the right bank during the two major transitions experienced during the burst and earth blanket construction, reveals about the possible locations of leakage ingress inlets.

Lets look at the ground water level fluctuations observed during right bank burst and earth blanket construction. The two incidents are considered separately.

(a) Right bank burst incident during October 1992

In October 1992, after about seven months of the first official impounding a burst in the right bank occurred due to the increased ground water level inside the right bank. In a previous section the detailed account of this incident has been provided. As a result the ground water level in the right bank dropped abruptly.

The Figures 4.3, 4.5 and 4.6 presented previously show how the right bank ground water level behaved during this incident as exhibited by the different observation wells and piezometers.

(b) Sealing of block 'X' during earth blanket construction

Similar ground water level behaviour was observed during the earth blanket construction. The following figures show the ground water level behaviour during this event.

- Figure 6.1 - Ground water level behaviour GW and MS series observation wells
- Figure 6.2 - Ground water level behaviour of RBS series standpipe piezometers
- Figure 6.3 - Ground water level behaviour SP series standpipe piezometers

As observed in the above graphs, all the observation wells and piezometers except GW 9, SP 53, SP 63, SP 64, SP 65, and SP 67 behave in a similar manner, showing an abrupt drop in the ground water level during the two events.

However those above mentioned GW 9 observation well and the five piezometers do not show any response and continue to follow the reservoir water level during the both events. In other words they are found to be intact by the two events which caused the whole right bank ground water level to drop abruptly. At the same time the bore hole GW 9 and SP67 piezometer continue to show a ground water level almost similar to the reservoir water level while the other four piezometers showing a level little lower than the reservoir water level through out.

When the piezometric head variation of the observation well GW 9 and above piezometers is compared with the two tank system it is found that it is equivalent to the piezometric heads shown by points lying along the connecting path of the two tanks. Therefore it can be postulated that in the real scenario, the above GW 9 and the above mentioned SP piezometers are lying along a leakage inlet channel to the right bank. Thus it shows a major leakage inlet is located very close to the dam in the dam right abutment lying along the stretch where GW 9, SP 53, SP 63, SP 64, SP 65, and SP 67 are located. The leakage ingress is supposed to take place through this inlet and travels to the common aquifer in the right bank and there it forms an extensive underground reservoir. The leakage is coming out from an outlet, another cavity opening, found in the other side of the underground reservoir as experienced at present.

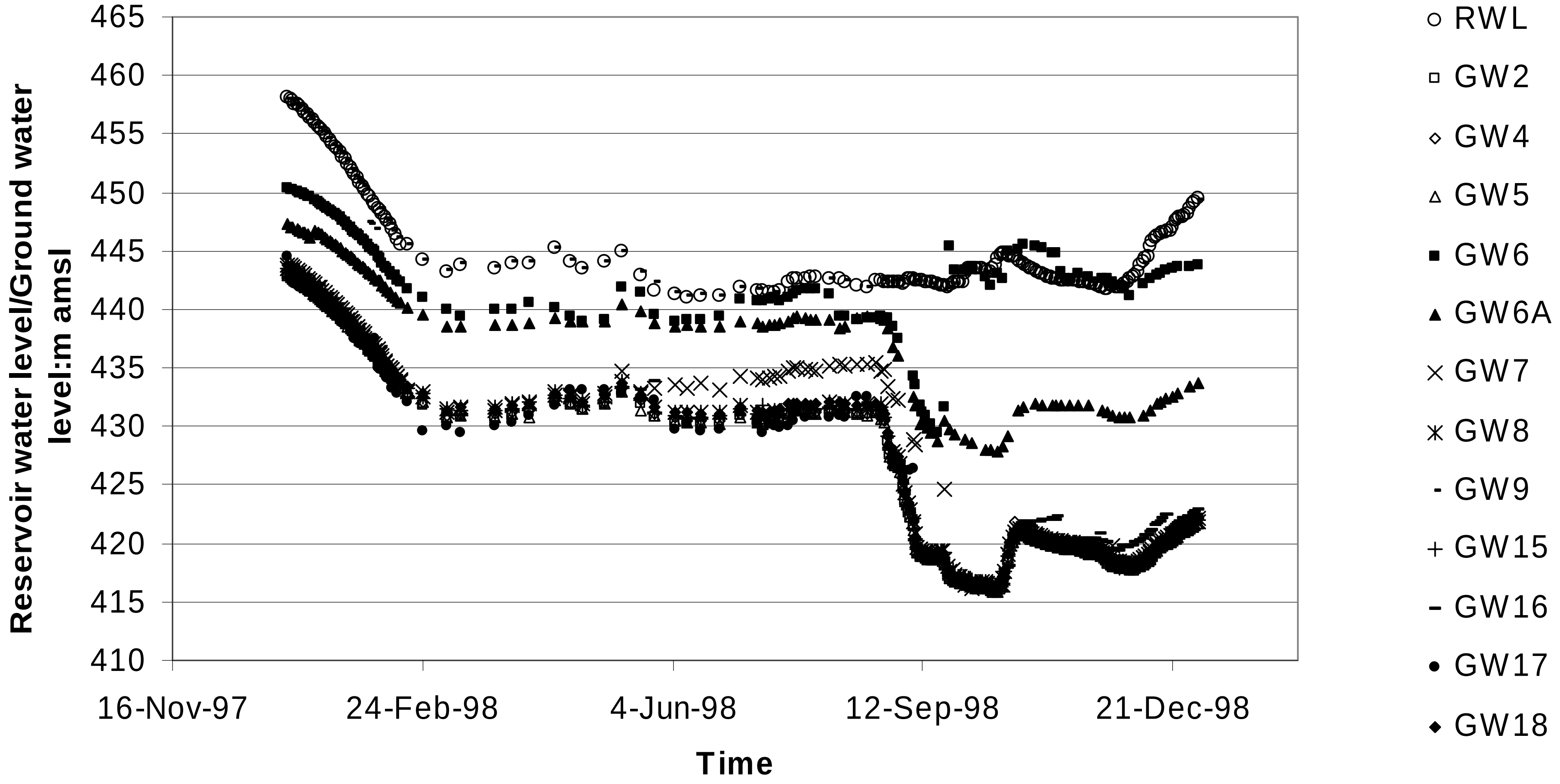


Figure 6.1 Ground water level behaviour shown by GW series observation wells during the earth blanket construction

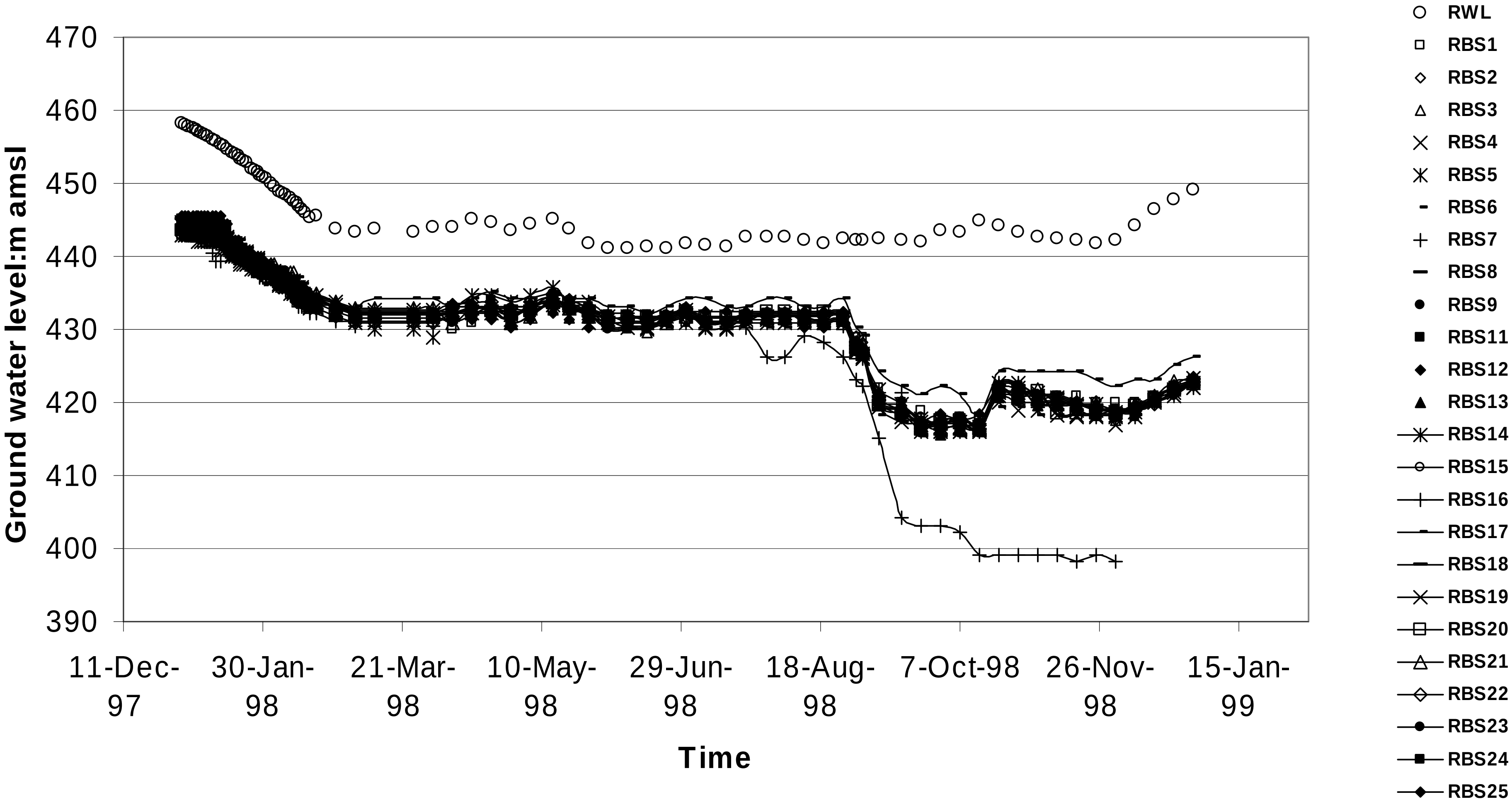


Figure 6.2 Ground water level behaviour shown by RBS series standpipe piezometers during earth blanket construction

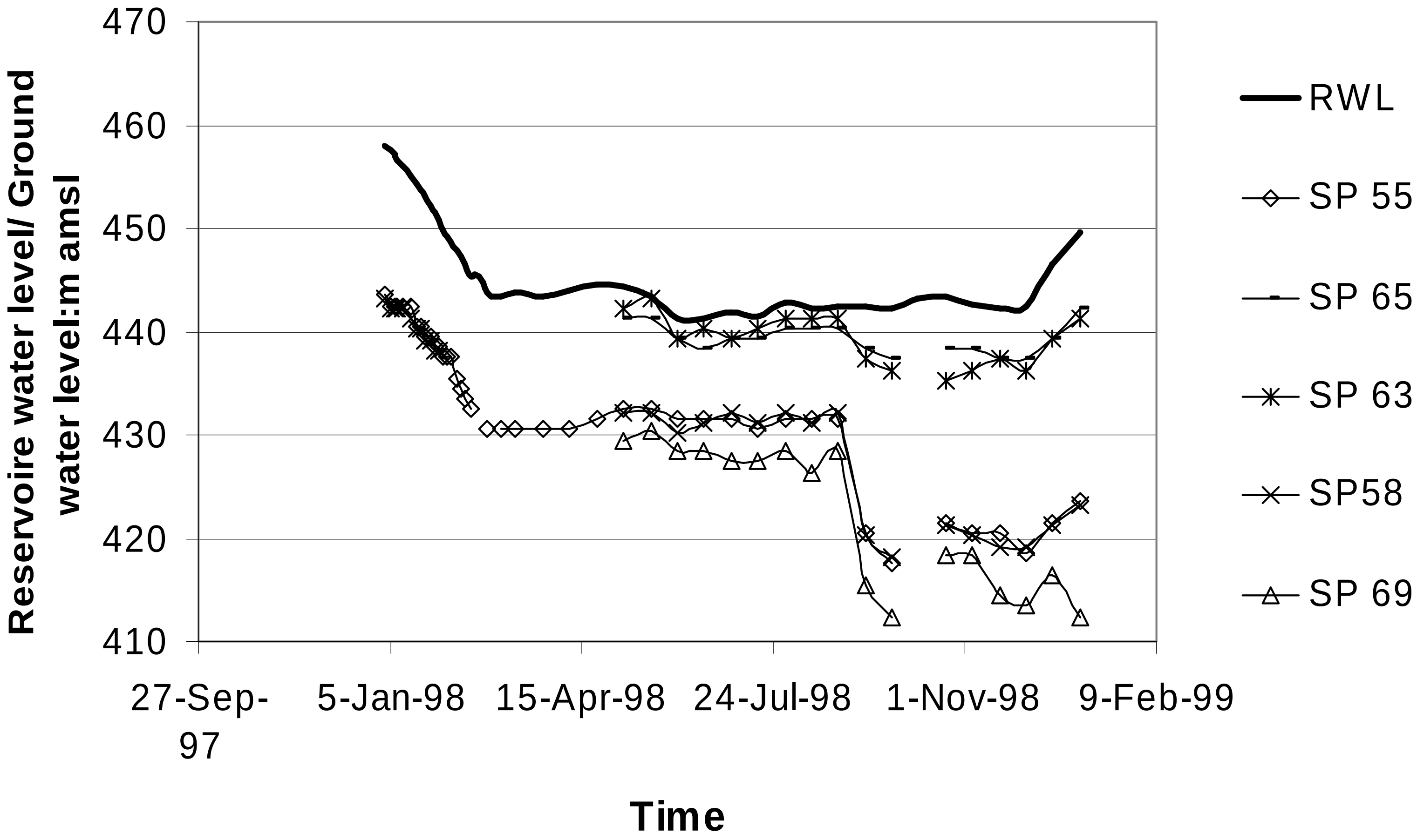


Figure 6.3 Ground water level behaviour shown by SP series standpipe piezometers during earth blanket construction

Similarly, earlier sealed cavity in block ‘X’ area during the earth blanket construction too could have directly fed the right bank aquifer. The behaviour of GW6, RBS 16 and RBS 17 suggest that block ‘X’ has a direct connection to this area. Immediate response of these observation well piezometers during earth blanket construction confirms it.

Further in the above ground water level variation plots of the two events, it can be seen that the abrupt drop of the ground water level is followed by a slight rise before the ground water level reaches stable levels. This is observed both during the burst and earth blanket construction. This phenomenon can be observed in a two tank system subjected to similar hydraulic conditions. And can be interpreted mathematically though the derivation is beyond the scope of this study. Importantly this phenomenon further strengthens the conclusion that the leakage ingress is taking place through few unique inlets.

6.6 Leakage mechanism

Therefore based on the so far conducted evaluation the reservoir leakage can be summarised as follows. The leakage ingress is supposed to take place through unique inlets and not from widely extended permeable zones as generally expected. Further these inlets are found to be located below the elevations 415-420m. It also confirms that there are no leakage ingress inlets lying over the upper slopes as once speculated.

Thus the reservoir water which ingress through these inlets travel in to the right bank interior and forms an extensive under ground reservoir which exhibits a common ground water elevation. The water from this underground reservoir leaks out through another cavity opening which is of same order as the leakage inlets.

Further with the earth blanket construction, one of the leakage inlets in the block `X` area, located on the river bed at a location about 500 m up stream of the dam which is accounting to about 40% of leakage ingress contribution got permanently sealed. It also showed that this inlet has been connected to the area in the right bank where GW 6, RBS 16, 17 are installed. Thus based on the above, the reservoir leakage mechanism flow vector diagram can be presented as shown in Figure 6.4.

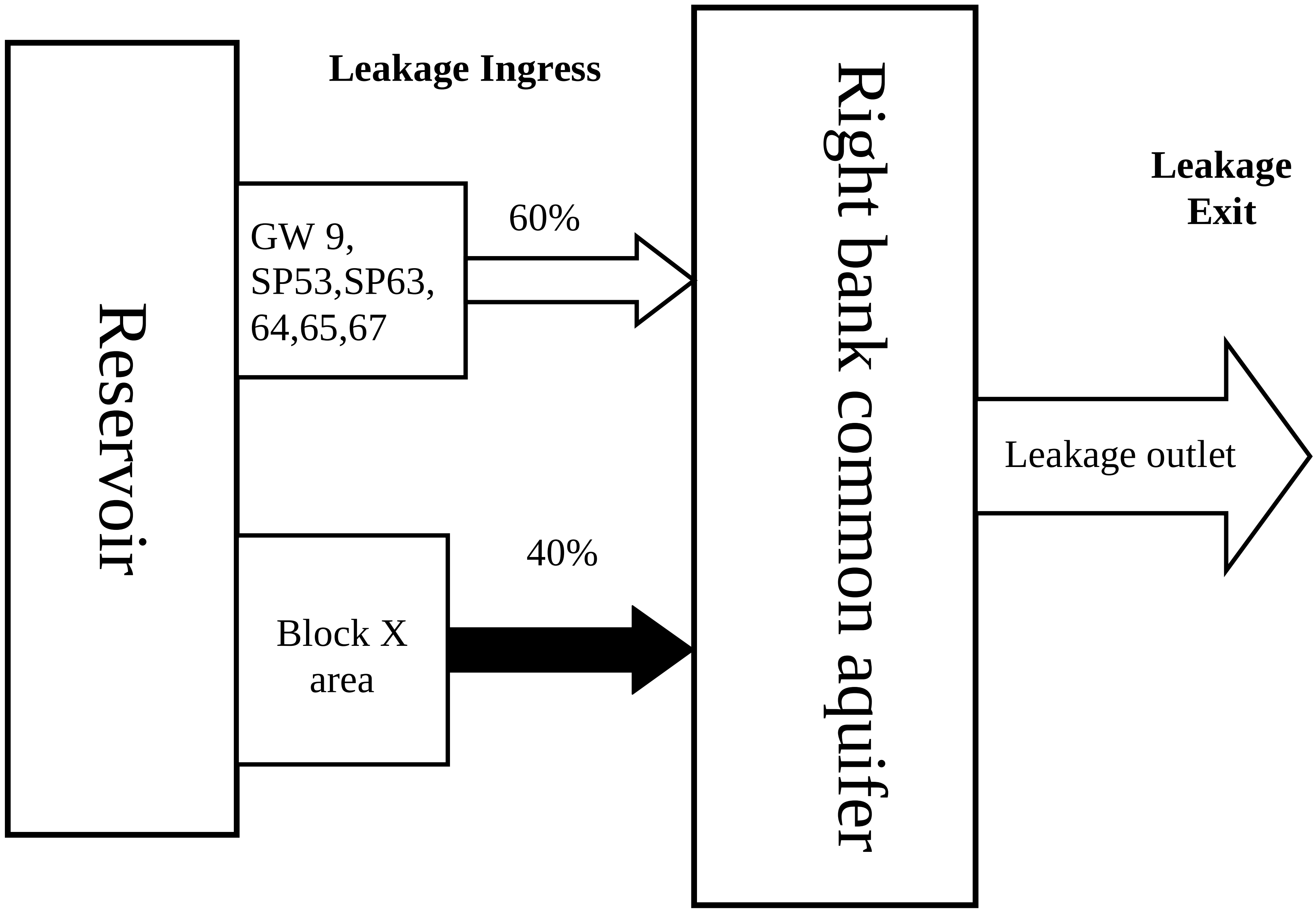


Figure 6.4 Leakage Mechanism flow vector diagram

Chapter 7

Summary and concluding remarks

7.1 General

Under this dissertation, on investigation of the water leakage mechanism of the karstified dam site, Samanalawewa, Sri Lanka a comprehensive evaluation of the Samanalawewa reservoir leakage problem was carried out.

The Samanalawewa reservoir developed a serious water leakage in its right bank during the initial impounding. The leakage posed not only economic problems due to lose of valuable water but also safety problems as the leakage phenomenon was associated with an increased ground water level situation in the right bank. The latter was causing to increase the ground instability and erosion potential. The large scale remedial exercises implemented, to seal off the leakage, incurring heavy costs in two instances failed indicating the complex nature of the problem. The failure of the remedial measures also indicated the incorrectness of the established leakage mechanism. Thus the problem also appeared as a major geotechnical engineering challenge in the recent times.

Therefore the necessity of establishing the exact leakage mechanism i.e. identifying the leakage ingress zones and leakage paths, through a detailed analysis, is of prime importance. It is also envisaged that the outcome of such a study will be directly applicable in future remedial measures planning in arresting the reservoir leakage.

The reservoir leakage problem history starts from the initial site investigation periods. During the project investigation phases and the dam construction stage, presence of a low and flat ground water level which is almost equal to the river water level, in the right bank was well evidenced. This was indicated by majority of the observation wells installed in the right bank. It also indicated that some kind of under drainage is taking place. In 1991 when the reservoir impounding was started for the first time, the leakage potential of the right bank was apparent with the initiation of the leakage in the form of a small spring located about 300 m down stream of the dam. At that instance, based on the available geological information, it was concluded that the leakage was taking place through the three main geological faults running across the right bank. Thus these faults, intersecting the river course up stream of the dam were considered as the main leakage paths with their intersecting zones with the river bed as the leakage inlets. Therefore as the first remedial attempt to seal off the leakage a deep grout curtain along the right bank ridge was planned. The main objective of the grout curtain was to cut off the main leakage paths flowing across the right bank. After detailed planning a 100 m deep 1300 m long grout curtain was built to act as a barrier against the leakage flow paths.

However, during the second impounding, immediately following the grout curtain construction, leakage reappeared notwithstanding the presence of a barrier across its path. The monitored ground water level behaviour indicated no hydraulic slope existing across the grout curtain. Apparently there was no change in the right bank ground water regime prevailed before the grout curtain construction. Then later on continuation of the reservoir impounding, a burst in the right bank occurred. With this burst incident the leakage increased by several folds. The burst incident also resulted in dropping of the right bank ground level and washing away a large amount of earth and rock material from right bank down stream face near the leakage outlet. Thus the first attempt of remedial measures failed to seal off the reservoir leakage.

Then after several years of studies to find a way to seal off the reservoir leakage, construction of an earth blanket over the suspected ingress areas in the river bed was considered as a suitable solution. In this method the objective was to arrest the leakage at the inlet itself. Having failed to cut off the leakage paths with the grout curtain, it was considered prudent to seal the areas in the river bed where main geological faults intersect. These areas were suspected to be acting as the leakage inlets (ingress areas). The main evidence available to support this theory was the geological findings. The results obtained from water chemistry analysis were also used to prove the connection between the leakage outlet and the suspected zones. This stretch was 700 m in length and located about 1 km up stream of the dam along the dam.

In 1998 on finalization of the preliminary works, construction of the earth blanket work was commenced. In this regard, prepared earth of pre-designed gradation was dumped over the suspected ingress areas using two, bottom open type dump barges. Dumping continued over the whole suspected area as planned. However even after sealing the whole suspected area with the earth blanket, no changes in the leakage flow rates or ground water levels were observed. Later the focus of the blanket construction was shifted to other areas out side the suspected zones. Thus when dumping earth on other areas along the rivers on a check basis, an area known as block 'X', lying about 500 m up stream of the dam, suddenly the ground water level and the leakage flow rate started to respond. The ground water level dropped and the leakage flow rate slightly reduced. As there was no further response whole earth blanket construction activities were suspended. However in general the earth blanket too failed to effectively seal off the reservoir leakage.

7.2 Failure of remedial measures

As so far observed basically both attempts of the remedial measures failed to seal off the reservoir leakage satisfactorily. In the first attempt with grout curtain no success made at all whereas in the second attempt some progress could be made by causing the right bank ground water level to drop. Further the second attempt also proved the suitability of the method provided the leakage ingress areas are known before hand.

In the case of the grout curtain, the failure to cut off the leakage can be attributed to one or all of the following reasons.

- There are no such leakage paths as predicted in the area treated
- The constructed grout curtain is having windows (open areas) hence failing to provide a effective sealing
- The grout curtain was not deep enough to cut off the leakage paths completely
- The leakage paths are lying else where

Similarly the failure of the earth blanket to seal off the leakage suggests that the identified ingress areas (suspected ingress areas) are totally incorrect and no ingress was taking place through them. Further the ground water level responses observed with the sealing of the block “X” area suggests that there are individual ingress (inlets) located out side the suspected ingress areas.

Incorrectness of the suspected ingress areas is mainly attributed to the fact that, it was not established on strong scientific evidence. The main tool used in this regard was the water chemistry analysis and this technique itself suffered from serious deficiencies due to the measuring accuracies, possible errors during sampling etc. Other supporting evidence used such as electrical conductivity measurements, temperature measurements too suffered from similar deficiencies.

The geophysical survey (seismic resistivity method) conducted over the suspected ingress area too could not find out the presence of any geological features which are supposed to be of assistance in leakage ingress.

In establishing the suspected ingress areas, it was purely based on the argument that the water from the reservoir, leakage outlet and from the piezometers RBS 4, RBS6 and RBS 10 were having similar water chemical characteristics. These three piezometers were supposed to be lying on the way between the ingress areas and the leakage outlet. Similar observations were also made among the temperature and electrical conductivity measurements. However there were several other observation wells, piezometers showing similar or slightly different characteristics but they were not considered as a part of the above.

Few years later after earth blanket construction, a study using Isotope techniques was conducted with the aim of establishing the leakage mechanism. This technique which is much superior to the water chemistry revealed that the ground water of all tested observation wells and piezometers were showing an equal signature irrespective of the location. No significant difference could be observed among those piezometers which were considered to be sitting on the leakage paths predicted.

Similarly in the ground water level-reservoir water level relationship evaluation conducted under this study, too did not reveal any significant difference in those piezometers, over the others which could help to prove that those piezometers are making a part of the leakage paths.

Thus in conclusion, the main cause of the failure of remedial measures to effectively seal off the leakage could be identified as the, incorrectness in the established the leakage mechanism. The adopted studies and investigations were also inadequate and they had not been able to provide sufficient evidence to establish the leakage mechanism.

7.3 Leakage mechanism

The correct understanding of the leakage mechanism of the reservoir, prior to attempting any remedial measures is of prime importance. Therefore as evaluated in the previous chapters, the leakage mechanism can be explained as follows.

Geologically the site, specially the right bank is a typical karstified site though it was not correctly identified during the initial stages. The right bank karstification is evidenced by the following facts.

- Highly porous nature prevailing underground as revealed by investigation holes with recorded drill rod drops, frequent water losses. Also the very high grout intake observed during grout curtain construction. Further, even after constructing a 100 m deep 1300 m long grout curtain no hydraulic across the right bank could be crated, indicating the porous nature of the right bank.
- Number of large caves formed by solution, found during dam right abutment excavations.
- Peculiar hydrogeological characteristics, specially the ground water level behaviour observed over a large area of the right bank, both before and after the impounding of the reservoir.

The right bank karstification has been aggravated by the tectonic activities to which the site has undergone. Mainly the three geological faults crossing the right bank has caused severe karstification in the middle of the right bank. This has been proved by the check holes which were drilled up to 200-250 m.

Thus the whole right bank interior has formed in to a highly porous, complicated and complex ground structure making it to act as an aquifer of confine nature. Further its behaviour resembles an underground reservoir. As observed with the ground water level behaviour, the right bank aquifer spreads over a wide area. The ground water level elevation observed in the right bank is same throughout the right bank. Also there are few observation wells and piezometers behaving independent of the reservoir water level changes and they represent isolated pockets with perched water table conditions within the right bank. They do not show any hydraulic connection with the right bank common aquifer. They behave independently and have no role in the leakage mechanism.

The swift reaction of the right bank ground water level to the reservoir water level as observed during the evaluated period, suggests that the reservoir and the right bank aquifer are in direct communication. The simultaneous response in all the observation wells to the reservoir water level changes, further confirms the hydraulic conductivity within the right bank as well as their direct connection to the reservoir.

When the relationship between the right bank ground water level and the reservoir water level is considered it shows a linear correlation between them. This linear correlation between them exists throughout except during two short transition events of water burst incident (1992) and the earth blanket construction (1998). Also the slope of the linear correlation, after the earth blanket construction is less than that before the construction.

The right bank ground water level behaviour and its correlation with the reservoir water level resembles the behaviour of a two interconnected tank system. Therefore the reservoir right bank system could be modelled using a two tank system. The similarities observed between the reservoir right bank system and the two tank model yielded following conclusions.

- The leakage inlets (ingress areas) in the reservoir are of concentrated nature, which is contrary to the general expectation of widely extended permeable zones lying along slopes. The leakage ingress is seemed to take place through unique inlets similar to openings in a tank.
- It can be further stated that these leakage inlets are to be found below the elevation 415–420 m amsl, and there are no leakage inlets or no ingress is taking place through the reservoir upper slopes.
- According to the equivalent cross sectional areas computed using the two tank model, the number of such inlets cannot be so many. It can be one or more outlets lying towards the reservoir bottom. Also the comparison of the equivalent

cross sectional areas of the leakage inlets and outlet suggest that they are of similar order.

Thus it is clear that the reservoir leakage ingress is taking place through a set of few inlets (ingress areas) located towards the reservoir bottom. Further when the right bank ground water level behaviour during the right bank burst incident and in the earth blanket construction period is considered, it shows that a major leakage inlet is lying up stream and close to the dam along the stretch where GW 9, SP 53, SP 54, SP 63, SP64,SP65 and SP67 are located.

In general, this study shows that very careful attention is required in selecting a site for water retaining structures, especially in the case of dams and reservoirs. The evidence of karstification needed to be thoroughly investigated as it may not be directly visible. Long term ground monitoring records need to be evaluated in understanding the hydrogeological influence. This is of importance since the karstification always associated with peculiar hydrogeological situations.

The failure of the two remedial measures suggests that the conventional methods used in water tightness improvements such as, grout curtains are no longer valid. Special and site specific remedial measures needed to be implemented after conducting thorough studies.

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